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Characterization of biochar produced by pyrolysis of biomass and co-pyrolysis of biomass and agricultural mulch film

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By

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A THESIS

Submitted in partial fulfillment of the requirements for the degree of
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Submitted by Ibrahim Cisse to fulfill a requirement for the degree of Master of Science in Sustainable Systems and accepted on behalf of the Rochester Institute of Technology by the thesis committee.

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Abstract

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Title: Characterization of biochar produced by pyrolysis of biomass and co-pyrolysis of biomass and agricultural mulch film

Agricultural wastes can be valuable materials because they are generated in large quantities all over the world and contain a variety of feedstocks. These feedstocks include dairy manure, food wastes, solid wastes and plastics. Current waste management techniques include landfilling and incineration, both leading to an increase in greenhouse gas emissions. However, alternative methods such as pyrolysis can present more sustainable pathways by transforming mixed wastes from the agricultural sector into value-added products such as biochar, bio-oil and syngas. Limited published literature has focused on producing biochar derived from co-pyrolysis of agricultural wastes with plastic wastes such as agricultural mulch films that are used for crop quality control. Most prior work has focused on fast co-pyrolysis of these materials, which favors bio-oil and syngas production rather than biochar. In this study, we explored the potential benefits of biochar generated from pyrolysis of agricultural solid wastes and co-pyrolysis of these wastes with agricultural mulch films plastics. We first produced and analyzed biochar derived from common biomass-based agricultural waste materials: hemp meal (HM), wood pellets (WP), pallet wood (PW) and hammer milled boxboard (HB) at two different temperatures (500 °C & 800 °C). These feedstocks were converted into biochar at laboratory conditions using a high temperature furnace with inert (N_2) environment. We further studied the presence of low-density polyethylene (LDPE) agricultural mulch films in both hemp meal and wood pellets feedstocks at the same temperatures and at three different blend ratios of 100:0, 95:5 and 75:25wt.%. It was found that the presence of plastics had minimal effects on the biochar quality of the wood pellets. After processing, all biochar materials except that derived from hemp meal had high organic carbon content (C_{org}) and hydrogen to carbon ($H:C$) ratio less than 0.7, indicating long-term stability. Assessments of soil enhancement properties and heavy metals present in the biochar were also conducted. Additional analysis was performed to determine the effect of mid-point temperature pyrolysis temperature on the quality of the biochar product. Finally, carbon sequestration and techno-economic analyses were conducted to quantify the potential sustainability benefits of deploying a commercial scale pyrolysis system at a single farm for on-site waste processing. The computed carbon sequestration impact factors (t CO_{2e}/t biochar) were consistent with prior studies modeling much larger systems, but profitability of biochar production was only achieved when processing wastes in a regional system including 10 times greater feedstock from surroundings farms, and assuming a relatively high biochar value of $500/t.

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CHAPTER 1

INTRODUCTION

As global food production continues to expand for the foreseeable future to meet demands of a growing population, associated wastes will also continue to increase. These wastes include both agricultural and municipal solid wastes. Qualified as one of the many sustainability challenges the world faces, waste management has become a central focus on a global scale in order to sustain and preserve natural resources (Trabold and Babbitt, 2018). Agricultural waste represents a fraction of municipal solid waste, yet it has important economic, environmental and social impacts. Therefore, reducing waste and optimizing its treatment is one way to make the food supply chain more sustainable (Garcia-Garcia et al., 2015)

The increase in food production in the agricultural sector will generate more wastes over the coming years, therefore raising concerns over adequate management. Agricultural waste streams are composed of both biomass-based and non-biomass types. Biomass-based wastes include crop residues, woody matter from trees and bushes, the inedible fraction of food produced that is not suitable for human or animal consumption, as well as other solid and liquid wastes including wooden pallets, boxboard and animal manure. On the other hand, non-biomass wastes include plastics, glass, and metal fabricated materials. With the broad diversity of waste materials that may be generated in the agricultural system, new management techniques and cutting-edge technologies are required to reduce risks associated with the environment, human health and society as a whole.

Conventional methods to manage waste generated in the agricultural system include landfilling and incineration. Both of these methods come with environmental problems that directly contribute to increase in greenhouse gas emissions and ultimately to climate change. These inefficient disposal practices can also be both economically and environmentally costly (Sintim & Flury, 2017). Other more sustainable techniques such as recycling and composting may not be effective. The challenges with recycling include limited understanding of the specific materials that are suitable for recycling, safety and poor quality of the recycling materials. Composting has the potential to convert biomass-based wastes into valuable soil amendments, but the time scale of the biological processes involved is on the order of weeks or longer. Also, the compost mixture must be well managed throughout the process to produce the desired end-product. Therefore, new approaches are needed to realize the long-term benefits of agricultural waste streams that include agricultural mulch films, woody biomass and crop residues while making end-of-life disposal more economically and environmentally sustainable, whilst maintaining ecosystem health.

Some of the more recently developed methods for managing agricultural wastes include anaerobic digestion and thermochemical processes such as pyrolysis, gasification, and plasma technologies. These different processes present wide ranges of benefits as well as challenges regarding waste handling. For example, anaerobic digestion (AD) is the biological conversion of organic waste through microbial activity in the absence of oxygen that produces biogas comprised of methane and carbon dioxide that can be used to generate electricity or heat (Molino et al., 2013). Anaerobic digestion (AD) offers viable options to industries to diminish carbon footprint by managing their wastes and revalorizing these wastes by converting them into usable energy. There has recently been a surge in growth of AD system deployment throughout the U.S. agricultural systems,

because this technology is well-suited for processing animal manure and food wastes that are in the liquid phase or can readily be converted into a slurry and pumped (Ebner et al., 2016). The challenge with AD is that the method is suitable for only certain organic wastes, cannot completely convert all the feedstock into biogas, and the effluent stream (often referred to as "digestate") requires further handling and treatment to avoid negative environmental impacts such as phosphorous run-off that leads to eutrophication (Xia & Murphy, 2016).

In the present study, we considered the problem of managing and valorizing agricultural waste streams that cannot reasonably be converted by existing biological processes such as composting or anaerobic digestion and present significant environmental and economic burdens, especially to smallholder farms that often operate with very thin margins. These biomass-based wastes include crop residues, woody biomass from trees, wooden pallets and cardboard boxes. Another particularly challenging waste material is agricultural mulch film (AMF), common throughout many agriculture regions to provide weed and insect control, increased soil temperature, and reduced evaporation and soil erosion. These benefits translate into reduced pesticide use, water conservation, and increased crop yield and quality. Plastic films used in conventional practice are relatively inexpensive and easy to install. However, after harvest, growers need to lift, remove and dispose of these materials in landfills or incinerators, which is costly and labor intensive (Sintim & Flury, 2017). Conventional low-density polyethylene (LDPE) mulch is typically used for only one growing season and cannot be recycled in most regions. Biodegradable mulch films are available, but adoption has been limited because of their slow degradation rate when tilled into the soil, resulting in small pieces of plastic film mixed with soil that take months to degrade or are blown away by wind and cause other environmental problems. Therefore, new approaches are

needed to realize the short-term benefits of agricultural mulch films while making end-of-life disposition more sustainable with long-term soil ecosystem health.

To deal with this significant waste management issue, another option to consider is thermochemical processing, broadly defined as high-temperature treatment under reduced oxygen conditions. Most of these thermochemical processes favor both liquid biofuel and syngas production, methods that strategically place biomass as a promising, sustainable option to meet global energy demands in the near future. For example, gasification involves more complex processes and has the ability to co-gasify different types of waste. However, the challenges with this method are that gasification is energy intensive, less proven on the commercial scale and leads to a dramatic reduction of the quantity of residues, which cannot be used for many applications, therefore not effective in valorizing the feedstocks (Arena et al., 2015).

Among the various thermochemical methods used for biomass waste management, pyrolysis technology can be especially well-suited for dealing with mixed waste. Pyrolysis consists of thermal decomposition of organic materials in the absence of oxygen to make highly stable and valuable materials such as biochar, bio-oil and hydrogen-rich biogas. The efficiency of the process is dependent on the quality of the different feedstocks, and specific co-products can be favored by judicious control of the pyrolysis process parameters. Biochar is a solid, carbon-rich material with production that can be controlled under so-called "slow pyrolysis" conditions that produces the greatest amount of char relative to the other co-products[1]. The characteristics of the biochar depend

[1] "Biochar" is often defined as carbonaceous material derived from thermochemical conversion of biomass that is intended for use as a soil amendment. Throughout this document, the terms "biochar" and "char" are used interchangeably, regardless of their intended end use.

on the peak temperature of the pyrolysis reaction, feedstock particle size and residence time in the reactor (Thangalazhy-Gopakumar & Adhikari, 2016). Producing biochar through pyrolysis has been deemed to be the most efficient option, especially when it comes to soil fertility, increasing carbon storage and decreasing greenhouse gases (Wu et al., 2012).

Agricultural mulch films and crop residues present notable potential for valorization whilst reducing waste and achieving circular economy via pyrolysis. However, different pyrolysis methods favor the generation of different by-products. Slow pyrolysis is used to generate biochar and pyrolysis gas and has the advantage of higher yields relative to fast pyrolysis (as much as 40 wt.%), but the disadvantage of producing a low-value energy product. On the other hand, the production of bio-oil is favored during fast pyrolysis, with biochar and the syngas the lower-yielding co-products (Xue et al., 2015). In fast pyrolysis, the biomass is decomposed thermally at moderate temperature in the absence of oxygen, allowing for a high rate of heat transfer to the biomass feedstock and a short residence time. A wide range of organic wastes can be used as feedstock to be converted into liquid bio-oil that can be further refined into energy fuels. Studies have demonstrated that co-pyrolysis methods of biomass feedstock with plastics such as polyethylene, polypropylene and polystyrene can increase oil yield and calorific value while reducing water content (Abnisa & Wan Daud, 2014).

Biochar produced by pyrolysis is very stable and has various applications in the agricultural sector that include soil amendment, as well as a carbon sequestration medium for achieving circular economy by utilizing and transforming wastes into value-added products. However, prior research involving co-pyrolysis of plastics and agricultural waste has focused primarily on bio-oil

production and recovery via fast-pyrolysis, while using this oil as a substitute to conventional crude oil such as petroleum for sustainable mobility. “Bio-oil is a mixture of oxygenated compounds; thus, it has to be catalytically deoxygenated via catalytic approaches before becoming biofuel” (Xue et al., 2015). The liquid has higher energy density than the original biomass and can be used directly as a low-quality fuel or further upgraded to transportation fuel and/or chemicals (Xue & Bai, 2018). Pyrolysis of feedstock provides good potential to manage two agricultural waste streams while producing value-added biochar and power (Ro et al., 2014). Agricultural plastic films and agricultural waste streams that include crop residues can have the potential of presenting large amounts of available energy. Due to these characteristics, co-processing of plastics with biomass appears to be a promising valorization route due to the enhanced process performance and greater process flexibility through methods such as pyrolysis (Lopez et al., 2018).

As summarized in Table 1.1, prior research on co-pyrolysis of various plastics and biomass has focused mostly on recovering valuable bio-oil for various applications. For example, co-pyrolysis of red oak with high-density polyethylene was investigated with an increasing temperature up to 625ºC. This particular co-pyrolysis method promoted the production of pyrolysis-oil, with further increase in pyrolysis temperature resulting in cracking of pyrolysis oil to form light gases rich in hydrocarbons (Xue et al., 2015). Co-pyrolysis of biomass and plastics wastes provides stability and homogeneity in the in the bio-oil as compared to the blending of individual oils. “Plastic is added to biomass during co-pyrolysis because it is hydrogen rich and biomass is a hydrogen deficient feedstock, therefore co-feeding with some hydrogen rich feedstock can be helpful in improving quantity and quality of oil yield” (Dewangan et al., 2016). Another literature reported that co-pyrolysis biochar derived from biomass such as pinecones and synthetic polymers had

higher calorific values compared to pyrolysis of biomass alone whilst having high synergistic effects (Brebu et al., 2010).

Other prior research reported the co-pyrolysis of plastic blends with lignin-rich materials such as woody biomass, agrarian biomass as well as waste from furniture such as cardboard. Researchers analyzed solid (char), liquid and gaseous products. The highest energy conversion in the case of the chars was obtained with the use of woody biomass and furniture waste. The average energy conversion efficiency values for char produced from waste furniture, woody biomass and straw biomass were 46.7, 45.7 and 40.6% respectively (Sajdak, 2017). Further studies included slow pyrolysis of pine cones with plastic materials, including Brebu et al. (2010), who investigated the pyrolysis of pine cones with different synthetic polymers such as polyethylene, polypropylene and polystyrene. The pyrolysis temperature was set at 500°C, and the authors performed comprehensive characterization of the biochar generated from of the process. A low ash content (<1%) was observed with the biochars produced from the co-pyrolysis of pine with synthetic polymers. There was also low sulfur content, making the chars attractive for use in incineration as a substitute to conventional charcoal.

Limited literature resources have emerged that focused on the biochar recovery from co-pyrolysis of biomass and agricultural plastic films that is of particular interest to our study. These wastes often include mixed plastic and organic wastes streams generated in food service operations such as cafeterias, where solutions may exist to process these streams independently but still have significant shortcomings. For example, composting can be effective for handling food waste, but also creates odor problems and materials take a long time to degrade. Therefore, new approaches

are needed to recover underlying value in mixed organic-plastic waste materials, while making the entire process more sustainable.

The current research has addressed the issue of agricultural waste management by investigating co-pyrolysis to convert mixed plastic and organic wastes at high temperature in the range 500 – 800 °C in a reduced oxygen environment. Experiments were conducted to assess only biochar as the primary byproduct of the co-pyrolysis reaction. Based on research gaps identified in a comprehensive literature assessment (Table 1.1), this research has attempted to answer the following compelling research questions:

- What are the properties of biochar produced by pyrolysis of common agricultural residues?
- How do these properties change when agricultural residues are co-pyrolyzed with polyethylene agricultural mulch film (AMF) material?
- Is biochar generated from co-pyrolysis of agricultural residues and polyethylene suitable for soil amendment?
- What are the potential carbon sequestration and economic benefits of a farm-based system for converting agricultural residues into biochar, with and without the addition of AMF material?

Addressing these research questions in the context of biomass-LDPE co-pyrolysis is part of a broader initiative to develop sustainable alternatives to conventional AMFs, including new biochar-bioplastic composite materials and “trigger” mechanisms that can accelerate degradation of AMF into its soil-compatible constituents at the end of the growing season. A graphical illustration of the overall project is provided in Figure 1.1. The focus of this thesis research is to quantify the potential of co-pyrolysis as an alternative end-of-life treatment option for agricultural

mulch film that is an advance over conventional practices of landfilling and incineration, in the event that primary goal of development of degradable biochar-bioplastic composite AMF materials cannot be achieved.

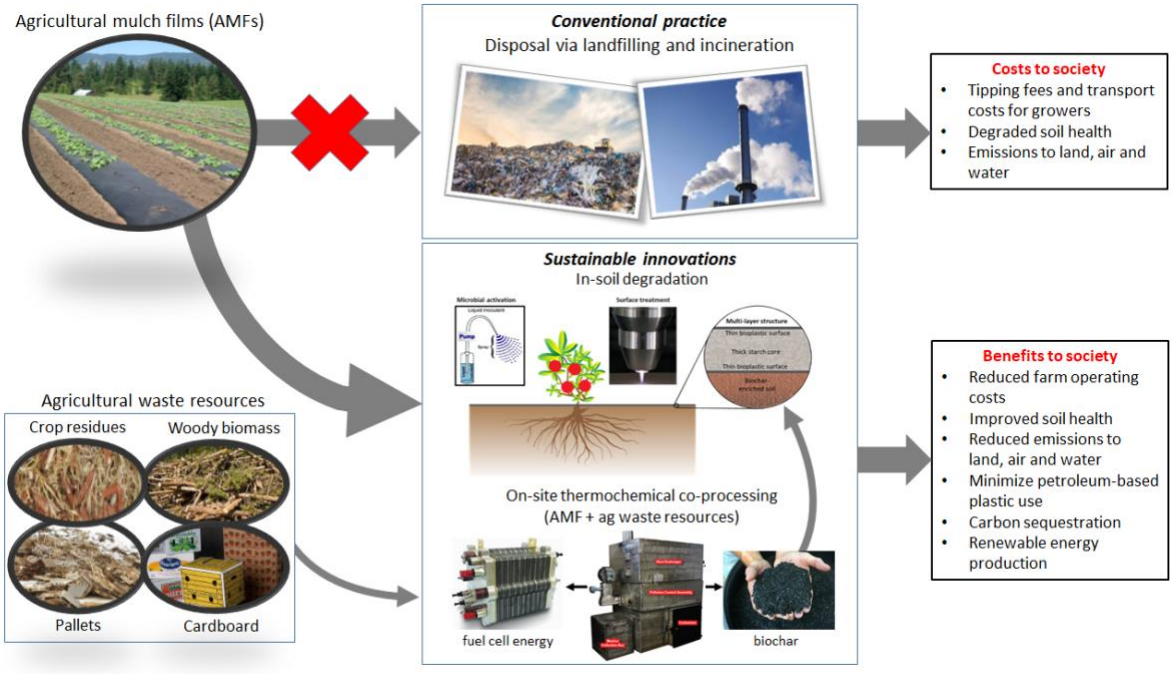

Figure 1.1 – Graphical abstract of project "*Degradable mulch films for sustainable agriculture*," funded by the Foundation for Food and Agriculture Research (FFAR).

Table 1.1 - Review of literature on co-pyrolysis of biomass with plastics

References	Feedstock		Summary of reported results
Authors	**Biomass**	**Plastic**	
Ro et al. (2014)	Swine Manure	Spent mulch films (SPM)	The study investigates the co-pyrolysis of swine solids and spent mulch films (SPM). Enough energy is generated at 25 % m/m with just 10% SPM. In the scenario where 10% SPM is used, surplus energy is generated for power generation. The biochars generated via co-pyrolysis of both feedstocks were analyzed by surface area and 1H NMR Spectra and were compared to the biochar produced from pyrolysis of swine solids.
Dorado et al. (2014)	Mixture (switchgrass, lignin, cellulose)	Polyethylene Polypropylene Low density polyethylene	This study aims to assess disposal of agricultural biomass wastes that include plastics and evaluate the fuels generated from co-pyrolysis of both feedstocks at 650°C via catalytic fast pyrolysis (CFP). The carbon yield of products generated from the co-pyrolysis process were compared with that of biomass alone, plastic alone. The study found that the presence of the different plastic polymers enhanced the increase in total aromatic yields.
(Zhang et al., 2016)	Lignocellulosic biomass (woods, grass, energy crops, and agricultural residues)	Waste polymers (plastics and waste tires)	The review provides overviews of the addition of hydrogen-rich co-reactant such as wastes plastics and waste tires in catalytic fast pyrolysis (CFP) to lignocellulosic biomass. The presence of these co-reactants can improve the yield of aromatic hydrocarbons. The study offers insight on waste polymers disposal from landfills, while solving environmental issues and further increase energy security.
Xue et al. (2015)	Red oak	High density polyethylene	Co-pyrolysis of red oak biomass and high-density polyethylene was studied via catalytic fast pyrolysis (CFP). The effects of pyrolysis temperatures and catalytic temperature (625 °C) were investigated. The promotion of pyrolysis oil was observed and its yield 57.6 w.t%. It was also found that the cracking pyrolysis oil due to the temperature caused the formation of light gases rich in hydrocarbons. A higher heating value up to 36.6 MJ/kg was observed and was cause by the additive effect of HDPE.
Dewangan et al. (2016)	Sugarcane bagasse (SCB)	Low-Density Polyethylene (LDPE)	Characterization of the different products (char & liquid) were conducted from co-pyrolysis of SCB and LDPE at the following blend ratios; 9:1, 3:1, 1:1 and 1:3. Analyses conducted to assess the liquid product include FT-IR, gas chromatography and mass spectroscopy. For the solid char, proximate and ultimate analyses and thermogravimetric analysis were conducted. The highest product yield co-pyrolysis of SCB/LDPE was 53.75% at 500 °C with 1:1 blend ratio.

Mullen et al., (2018)	Switchgrass	Polyethylene	The study enhances the production of aromatic hydrocarbons via fast co-pyrolysis with HZMS-5 as a catalyst. The two feedstocks used were switchgrass and polyethylene at (1:1 w:w). The pyrolysis temperature was 650°C. Mass spectroscopy and gas chromatography were performed to assess the products. Results show that blending of switchgrass and high-density polyethylene favored the production of aromatic hydrocarbons.
Dorado et al., (2015)	Switchgrass	Polyethylene	Tail gas reactive pyrolysis was used to assess the pyrolysis of switchgrass with polyethylene (4-37%) and switchgrass at temperatures ranging from 400 to 570°C. The formation of waxy solids produced in the process was reduced. However, mostly noncondensable gases along with highly deoxygenated and aromatized pyrolysis oil were produced under 70% tail gas atmospheric conditions.
Čepelioɨullar & Pütün (2014)	Cotton stalk, hazelnut shells, and sunflower residues	Polyvinyl chloride and polyethylene terephthalate	Co-pyrolysis of different agricultural wastes and plastic wastes were conducted to assessed (1:1; w:w). In this study, experiments were conducted at a heating rate of 10°C/ min to a maximum temperature of 800°C. The solid char and liquid product were assessed via scanning electron microscope (SEM) in order to determine the change in the surface. Characterization of the liquid product includes FT-IR. Analysis. It was found that presence of PET almost doubled oil yields as compared to other plastic types.
Tai & Chen (2016)	Rice straw	PET & PLA	Products derived from co-pyrolysis of PET, PLA and rice straw via proximate analysis and thermogravimetric analysis were conducted to assess the kinetic parameters of the products during the overall pyrolysis reactions. It was found that the maximum decomposition temperatures and activation energies that was needed to pyrolysis PLA and PET was reduced in the presence of rice straw.
(Oh & Seo, 2019)	Rice straw	PET	Characteristics of biochar produced from co-pyrolysis of PET and rice straw was examined and its performance as a sorbent was assessed for various U.S. EPA priority pollutants such as chromate and selenate. The pyrolysis temperature ranged from 550 to 900°C. Essential biochars physical properties were also assessed. The results demonstrates that the biochar derived from the mixture of PET and agricultural wastes may be favorable to enhance the quality of the biochar as a sorbent.

Bhattacharya et al., (2009)	Pine wood	Polystyrene (PS), HDPE,PP	Fast co-pyrolysis of wood and different plastic feedstocks (PS, HDPE & PP) was conducted with a 50:50, w/w, pine wood/plastics. The bio-oil generated from the process was accessed. The data showed that in biochar pyrolyzed 400 °C, carbon content was about 70%, hydrogen content just about 4%, oxygen content ranging from 24% to 25%, nitrogen about 1% and the sulfur content could be considered negligible. Increasing the biochar production temperature resulted in an increase of over 3% in carbon and a decrease of about 2.5% in oxygen and 1% in nitrogen.
Xue et al., (2016)	Cellulose, xylan & milled wood lignin	PE	The interaction of co-pyrolysis between cellulose, xylan, milled wood lignin and PE (50:50; w:w) was investigated under catalytic conditions. A higher heating value of the pyrolysis oil was observed as well as an increase in C and H due to the presence of PE.
Xue & Bai (2018)	Corn Stover (CS)	Polyethylene	Synergistic interactions between polyethylene and acid pretreated corn stover were investigated in the presence/ absence of zeolite catalyst. A reduction in char yield and increase in both the yield and quality of CS-derived pyrolysis oil were also observed.
Brebu et al. (2010)	Pine cone	Synthetic polymers (PE,PP,PS)	Co-pyrolysis of pine cone with PE, PP and PS was investigated at a temperature of 500°C. The oils and the chars generated from the process were accessed via elemental analysis, thermogravimetric analysis as well as gas chromatography. The chars had high calorific values and low ash and sulfur content suggesting suitability for various applications.
(Yang et al., 2016)	Cedar wood, sunflower stalk and fallopia Japonica	LDPE	Co-pyrolysis of LDPE and three different types of biomass in a dropdown tube reactor was investigated. Pyrolysis temperature ranged from 500 to 600 °C. It was found that the maximum oil relative yield in the case of co-pyrolysis process was obtained at 600 °C, which was significantly higher than the optimum temperature of biomass or LDPE pyrolyzed alone.

CHAPTER 2

BIOCHAR PRODUCTION & CHARACTERIZATION

In this chapter, the methods used to produce and characterize the biochar using slow pyrolysis are presented. The pyrolysis and co-pyrolysis experiments with different feedstocks described below were conducted over a range of temperatures (500 - 800°C) and involved the thermochemical decomposition of wastes in the absence of oxygen, enabling production of carbon-rich biochar with potential applications beyond just fertilizer for soil health. Other usages include carbon sequestration agent, adsorbent, pharmaceutical applications, energy production for heat and power, as well as building materials. The pyrolysis processes and the type of feedstock materials are important factors in determining the characteristics of the product biochar and its ultimate applications.

2.1 Experimental Materials

In this study, we aimed to understand the characteristics of biochar generated from the co-pyrolysis of different agricultural waste streams coupled with low-density polyethylene (LDPE) mulch films. Typical waste feedstocks generated in agricultural operations in western New York State were identified by local growers, with detailed quantitative data provided by a farm market located in Western NY. This farm confirmed generation of four main waste types: crop residues, woody biomass from trees and bush trimming, wooden pallets and cardboard. The general information was used to identify four specific organic feedstocks and one agricultural mulch film to be converted to biochar in all pyrolysis and co-pyrolysis experiments:

- **Hemp meal:** The representative crop residue was the biomass remaining after a supercritical carbon dioxide extraction process. Hemp flowers were harvested, dried to approximately 10% moisture, milled and run through a carbon dioxide extractor that separates and isolates the majority of CBD oil. The hemp crop was grown on a farm in western New York State.
- **Wood pellets:** Hardwood pellets, typically used as fuel for barbeque grills, were purchased from a local store; brand name "PIT BOSS" (Edmonton, AB, Canada). The pellets were 100% hardwood pellets competition blend, which means they have no flavors, spray scents, glue or chemicals. It is a mixed blend of maple, hickory and cherry woods.
- **Pallet wood:** Plain wooden pallets broken into roughly 20-75 mm pieces were obtained from Aries Clean Technologies (Franklin, TN, USA). The company uses this same feedstock material to produce "Aries Green®" biochar, sold commercially as a soil conditioner. The company provided biochar characterization data (Appendix A).
- **Hammer milled boxboard:** The cardboard samples were derived from virgin, uncoated boxboard obtained from a Staples, Inc. distribution facility in Montgomery, NY. The boxes were selected at random from a large stack of unused boxes intended for shipping products to retail stores. They were ground, homogenized and aerated in a "13 Series" pneumatic discharge hammer mill manufactured by Schutte-Buffalo Hammermill, LLC in Buffalo, NY.
- **Low-density polyethylene (LDPE) films:** Black plastic garden mulch was obtained from Ken-Bar in Rochester, NY. The plastic film offers advantages to crops such as weed control, increased soil temperature, reduced evaporation of soil moisture and less nutrient

leaching. The material was taken from a 4’ x 4000’ (1.2 x 1200 m) roll with thickness of 1 mil (25.4 μm).

Figure 2.1– Biomass materials used as feedstock for pyrolysis and co-pyrolysis experiments: (a) wood pellets (WP); (b) hemp meal (HM); (c) pallet wood (PW); (d) hammer milled boxboard (HB)

2.2 Experimental Methods

2.2.1 Biochar production

A high temperature furnace (CM Furnaces Inc.) with a coupled microwave generator (SAIREM SAS) was used to conduct the pyrolysis and co-pyrolysis experiments (Figure 2.2). The system is designed to maintain maximum temperature of 1700°C with the microwave generator, but this feature was not used for any of the research described in this document. In this study, temperatures were varied from 500 to 800°C using conventional resistive heating elements. During all runs, nitrogen was used as the inert gas atmosphere, and there was also flow of water through the system for cooling. The system can hold up to five 100 mL porcelain crucibles obtained from Fisher Scientific that can withstand temperature up to 1150°C. In the interest of safety and to minimize production of bio-oil, two or three crucibles were used per run. The ramp rate and maximum temperature hold time were fixed at 10°C/min and 1 hour, respectively. These parameters were used based on previous studies conducted on biochar production (Frias Flores, 2020).

Biochar was produced from pyrolysis of wood pellets, hemp meal, pallet wood, and hammer milled boxboard, as illustrated in Figure 2.1. The second part of the experimental campaign involved co-pyrolysis of hemp meal and wood pellets with low-density polyethylene AMF at biomass:plastic mass ratios of 95:5% and 75:25%. These ratios were chosen due to the very low amount plastic films availability after the growing season and the large amount of biomass waste relative to AMF waste. The mass of raw organic content in each crucible varied across all experiments because of the difference in feedstock densities. To maintain consistency, each material was entirely filled to the brim of the crucibles. The crucibles were then placed inside the furnace, where they were heated at 10^{o}C/min until the desired target temperature was reached. After the 1-hour hold time,

power was turned off and the system was allowed to cool to approximately 250°C before total shutdown when nitrogen gas and cooling water were also turned off. Each biochar sample was placed in an air-tight plastic container and labeled specifically according to the nomenclature provided in Table 2.1. This applied to the pyrolysis of the different organic biomass wastes, and the co-pyrolysis of these biomass wastes with low-density polyethylene (LDPE) films.

Figure 2.2 - Furnace for biochar production under oxygen-free conditions

Table 2.1 – Nomenclature for biochar samples produced with different biomass feedstocks at various temperatures and LDPE blend ratios.

Sample #	Name	Biomass feedstock	Blend ratio (Biomass: LDPE)	Pyrolysis Temp (ºC)	Mode [I]
1	HM	Raw Hemp Meal	N/A	N/A	Mode 1
2	HM500C	Hemp Meal	100:0	500	Mode 1
3	HM800C	Hemp meal	100:0	800	Mode 1
4	HMFM (95/5) 500C	Hemp Meal	95:5	500	Mode 1
5	HMFM (95/5) 800C	Hemp Meal	95:5	800	Mode 1
6	HMFM (75/25) 500C	Hemp Meal	75:25	500	Mode 1
7	HMFM (75/25) 800C	Hemp Meal	75:25	800	Mode 1
8	WP	Raw Wood Pellets	N/A	N/A	Mode 1
9	WP500C	Wood Pellets	0:100	500	Mode 1
10	WP650C	Wood Pellets	0:100	650	Mode 1
11	WP800C	Wood Pellets	0:100	800	Mode 1
12	WPFM (95/5) 500C	Wood Pellets	95:5	500	Mode 1
13	WPFM (95/5) 650C	Wood pellets	95;5	650	Mode 1
14	WPFM (95/5) 800C	Wood Pellets	95:5	800	Mode 1
15	WPFM (75/25) 500C	Wood Pellets	75:25	500	Mode 1
16	WPFM (75/25) 650C	Wood pellets	75:25	650	Mode 1
17	WPFM (75/25) 800C	Wood Pellets	75:25	800	Mode 1
18	HMB	Raw Boxboard	N/A	N/A	Mode 1
19	HMB500C	Boxboard	100:0	500	Mode 2
20	HMB800C	Boxboard	100:0	800	Mode 2
21	PW	Raw Pallet Wood	N/A	N/A	Mode 2
22	PW500C	Pallet Wood	100:0	500	Mode 2
23	PW800C	Pallet Wood	100:0	800	Mode 2

[I] Mode 1 analysis including all in-house measurements (yield, pH, surface area by nitrogen adsorption) and International Biochar Initiative (IBI) standard measurement suite provided by Control Laboratories (Watsonville, CA, USA).

Mode 2 analysis includes all Mode 1 measurements except in-house specific surface area by nitrogen adsorption.

2.2.2 In-house surface area and pore size measurements

The NOVA e-Series Model 4200 obtained from Quantachrome Instruments (Figure 2.3) was used to measure surface area and pore size. This system has four analysis stations that are able to determine Brunauer-Emmett-Teller (BET) specific surface area measurements (in m^2/g), pore size distribution and pore radius by nitrogen adsorption analysis at 10 psi (69 kPa).

Figure 2.3 - Quantachrome NOVAe system for surface area and pore size measurement

Four 9 mm diameter borosilicate glass tubes with no bulb were obtained from Anton Paar, the Austrian company that acquired Quantachrome in 2018. Approximately 0.2 g of biochar was

placed inside each tube. To perform the surface area measurements, the samples were first degassed under vacuum for 24 hours at a temperature of 105°C. The samples were then taken out the next day, and the net weight after drying was recorded and entered manually into the NOVA Win software to run the analysis. The tubes were then placed in the analysis stations of the Quantachrome instrument, with liquid nitrogen (N_2) added as a coolant medium. The analysis ran for 24 hours and the results were recorded the next day. Results such as the surface area, pore size and pore radius were recorded based on multi-point BET theory (Brewer et al., 2014).

2.2.3 In-house pH measurements

The measurements followed the method of Rajkovich et al. (2012), also used as part of International Biochar Initiative (IBI) standard biochar measurements as described in Section 2.2.4. The biochar pH values were obtained after first preparing a mixture of 1.0 g of biochar in 20 mL deionized (DI) water and placing in a shaker for 1.5 h to ensure sufficient equilibration between DI water and biochar surfaces (Figure 2.4). Samples were allowed to sit 5 minutes after shaking before pH values were recorded via electric conductivity with a BIOSTAT-2 pH sensor (Figure 2.5). The pH calibration sensor has a +/- 0.05 instrument uncertainty.

Figure 2.4 - Barnstead Lab-Line Q4000 Incubator Shaker

Figure 2.5 - pH measurement system with electrical conductivity probe

2.2.4 International Biochar Initiative (IBI) Protocol Testing

All raw feedstocks and biochar samples were characterized by Control Laboratories (Watsonville, CA) based on an International Biochar Initiative protocol that is commonly used for biochar intended for soil amendment applications (International Biochar Initiative, 2015). The three types of measurements made as part of this standard, as well as the associated methods, are outlined below. Raw datasheets delivered by Control Laboratories for each biochar sample analyzed are provided in Appendix B.

Basic Utility Properties

Moisture, total ash, and volatile matter were determined based on ASTM D1762-84 standard test chemical analysis for wood charcoal (ASTM 2007). Organic carbon, hydrogen-to-carbon ratio (H:C), total nitrogen and carbonates were determined by dry combustion-elemental analyzer following method ASTM D4373 (ASTM 2007). Electrical conductivity and pH measurements were determined following the test method proposed by Rajkovich et al. (2012). Surface area by the butane activity correlation method was conducted using the method reported by McLaughlin et al. (2012).

Advanced Analysis and Soil Enhancement Properties

Mineral nitrogen, nitrate and ammonia were determined using the method of Rayment & Higginson (1992). Total phosphorous and potassium followed methods used by Enders & Lehmann (2012).

Toxicant Assessments

Concentration of metals (arsenic, cadmium, chromium, cobalt, copper, lead, molybdenum, nickel, selenium, zinc, boron, sodium, iron, chlorine and manganese) were determined following test methods for the examination of composting and compost (TMECC) by US Composting Council and US Department of Agriculture (2001). Mercury was determined following US EPA 7471 method (Environmental Protection Agency, 2007).

CHAPTER 3

EXPERIMENTAL RESULTS AND DISCUSSION

As summarized in Table 2.1, four different biomass feedstocks (hemp meal as representative agricultural crop residue, wood pellets as representative woody biomass, pallet wood and hammer milled cardboard) were converted into biochar under N_2 atmosphere at maximum temperatures of 500^{o}C and greater. In this chapter, the results of the biochar characterization analysis are presented: pyrolysis of all biomass feedstocks at 500 and 800^{o}C (Section 3.1); co-pyrolysis of hemp meal and woody biomass at these same temperatures in combination with low-density polyethylene mulch film with biomass-to-LDPE mass ratios of 95:5 and 75:25 (Section 3.2); and expanded analysis of woody biomass and LDPE biochar properties as a function of maximum co-pyrolysis temperature (Section 3.3). Finally, in Section 3.4, we provide a direct comparison of in-house measurements of pH and specific surface area with those provided by Control Laboratories (Appendix B).

3.1. Biochar produced by pyrolysis of agricultural waste biomass

It is well known that pyrolysis processing conditions such as maximum temperature, ramp rate (^{o}C/min) and residence time affect the amount of biochar that can be obtained from any feedstock, and largely dictate the properties of the final material product. The properties of the raw feedstock materials and associated biochar from pyrolysis experiments (i.e., without blending with LDPE) are summarized in Tables 3.1 and 3.2, with the full characterization data sheets from Control Laboratories provided in Appendix B. In each case, the maximum pyrolysis temperature was set at either 500 or 800^{o}C, with fixed ramp rate and residence time of 10^{o}C/min and 1 hour, respectively. The most important biochar property results are briefly discussed below in the

context of prior published data, primarily as presented in the comprehensive review paper of Weber and Quicker (2018).

Average yield

As described in Chapter 2, the pyrolysis furnace was operated with two or three crucibles per run, in the interest of safety and to minimize production of bio-oil. Each of the average yield values reported in Table 3.1 were computed from three to five individual mass yield measurements (from one or two furnace runs) defined as:

$$\text{Mass yield} = \frac{(Filled\ crucible\ mass\ after\ pyrolysis - Crucible\ mass)}{(Filled\ crucible\ mass\ before\ pyrolysis - Crucible\ mass)}\ x\ 100 \qquad \text{(Eq. 3.1)}$$

As expected, for each biomass feedstock, the yield decreased with increasing temperature as more of the base material was converted into hydrogen-rich syngas and/or bio-oils, leaving less of the carbon content in the solid biochar phase. The overall range of yields is consistent with the analysis of Weber and Quicker (2018) that showed for typical intermediate temperatures of 500 to 800°C mass yields in the range of 20 to 35% for both woody and non-woody biomass feedstocks. The present results indicate that hemp meal produced the highest yields, with the other three feedstocks producing nearly the same yield around 28% at 500°C. At 800°C, pallet wood biochar yield was 25%, whereas both wood pellets and hammer milled boxboard dropped to about 22%.

Total ash

The yield data need to be evaluated in combination with the total ash measurements, because high ash content (mostly comprised of inorganic compounds present in the original biomass) generally indicates low biochar quality that may limit use in higher value industrial applications. As noted by Weber and Quicker (2018), high biochar ash content correlates to high starting biomass ash content, and the results in Table 3.1 agree with this expected trend. It can also be seen that hemp meal biomass and biochars all have very high ash content of 13.5 to 44%, which also helps explain the relatively high mass yields that exceed measurements for the other three feedstocks. The relatively low ash content measurements (<4%) for the two woody biomass feedstocks (wood pellets and pallet wood) are consistent with the results of Weber and Quicker (2018), as is the general trend of higher ash content at higher pyrolysis processing temperature. The ash content measured for hammer milled boxboard at 800^{o}C (16.0%) seems to be unusually high and may require further experimentation to better understand this phenomenon.

Moisture content

Due to the very high temperatures encountered in the pyrolysis process, all water is removed, making the final biochar moisture content essentially zero. However, once the material cools it begins to adsorb some moisture from the surrounding atmosphere and in fact for commercial biochar production, some water is beneficial to prevent potential fire accidents. For most of the biomass feedstocks and processing temperatures summarized in Table 3.1, the measured moisture content was less than 6%, about what would be expected for biomass materials such as food waste that are processed using industrial dehydration equipment (Schroeder et al., 2020). The only

exception was hammer milled boxboard biochar processed at 800°C, where the relatively high moisture content of 12.8% may be related to the high total ash measurement mentioned above.

Bulk density

The bulk density is an important parameter of biochar in regard to handling and transport on a commercial scale, but also when considering it as a potential replacement for common carbonaceous materials used in industry, such as carbon black and granular activated carbon (GAC). For agricultural applications, low bulk density is often favored because water holding capacity and soil aeration are primary considerations. It is expected that bulk density would decrease with increasing temperature, as more gases devolatilize from the solid biomass structure leaving the porous biochar material behind (Weber and Quicker, 2018). However, the current data in Table 3.1 generally do not follow this trend. In the case of both wood pellets (WP) and pallet wood (PW), the bulk density actually increased upon increasing processing temperature from 500 to 800°C, and for hemp meal (HM) the measurements were nearly equivalent (192.2 and 187.4 kg/m^3). Only in the case of hammer milled boxboard (HB) was a significant decrease in bulk density observed upon increasing temperature from 500 to 800°C, and the very large change from 126.5 to 40.0 kg/m^3 may again be correlated to the relatively high moisture content and total ash measurements mentioned above.

Hydrogen-to-carbon ratio (H:C)

Per guidelines set forth by the International Biochar Initiative (IBI), for a biochar product to be considered suitable as a soil amendment, the material must have a hydrogen-to-carbon ratio less than 0.7 (Enders & Lehmann, 2012). This parameter indicates stability in the biochar as lower

values of H:C indicate deformation of functional groups and formation of aromatic structures in the biochar product (Wei et al., 2020). This makes the biochar more recalcitrant, able to resist oxidation for many years if applied onto the field. Among the biochar materials generated from the four biomass feedstocks summarized in Table 3.1, all had H:C < 0.7 except for hemp meal biochar at 500°C which was slightly above 0.7 (H:C = 0.71). Woody biomass feedstocks of wood pellets (WP) and pallet wood (PW) produced biochars with very low H:C at 800°C (0.23 and 0.26, respectively), indicating more stability in the biochar and presenting good potential for usage as a soil amendment, especially with high organic carbon content. The measured values of H:C at both 500 and 800°C align well with the ranges of values reported by Weber and Quicker (2018) for biochar produced from woody biomass. The higher H:C values measured for hemp meal and hammer milled boxboard correlate better to the ranges of values reported for residues from crops such as corn, wheat and straw.

pH

The pH value is a critical consideration for agricultural applications, particularly when being used as a soil amendment. Weber and Quicker (2018) have noted that raw biomass is often slightly acidic or mildly basic with pH values typically in the range of 5 to 7.5. The current results for raw hemp meal (HM) and hammer milled boxboard (HB) are consistent with this range, but surprisingly wood pellet biomass showed a relatively high starting pH value of 12.4. “Because functional groups detached during pyrolysis (carboxyl, hydroxyl, or formyl) are predominantly acidic in nature, the remaining solid becomes more basic as these more functional groups are released during the pyrolysis reaction” (Weber and Quicker 2018). In the cases of HM and HB feedstocks, large increases in pH were observed, especially upon increasing processing

temperature to 800ºC. In the case of hemp meal, the relatively high pH of biochar produced at 500 and 800ºC (12.0 and 12.6, respectively) may be in part attributed to the high content of ash which is alkaline in nature. However, the wood pellet (WP) results seem to contradict the general trend reported by Weber and Quicker (2018), because the pH dramatically *decreased* during the conversion to biochar. As discussed further in Section 3.4, it is believed these measurements from Control Laboratories may be suspect due to inconsistency with parallel in-house pH measurements conducted.

Electrical conductivity (EC)

EC is important especially for salts sensitive plants. It is based on the principle that solutions with a higher concentration of salts have a greater ability to conduct an electrical current and heavily dependent on type of feedstock and pyrolysis temperature (Cheng et al., 2006). Weber and Quicker (2018) have also demonstrated that electrical properties of biochar change throughout the carbonization process, with a decrease in functional groups generally leading to higher electrical conductivity at higher processing temperature. The EC results for all four biomass feedstocks are consistent with this trend. It is interesting to note that the highest electrical conductivity values correlate with relatively high total ash content measured for hemp meal (HM) biochar at 500 and 800ºC, and hammer milled boxboard (HB) at 800ºC (Rehrah et al., 2014). (Tomczyk et al., 2020) reported that differences in the EC of biochar produced using different feedstocks result from differences in their electrical conductivity. The results displayed in Tables 3.1 and 3.4 show the correlation with increasing temperature and higher EC values being from HM800C and HMFM (75/25) at 800ºC with values of 9.50 and 7.61 ds/m respectively. All the biochar EC values are

within the range of what has been shown in most literatures from 0.4 dS/m to 54.2 dS/m (Cheng et al., 2006).

Specific surface area

Specific surface area (SSA) is a very important parameter for many applications of biochar, because this parameter strongly influences the capacity of the biochar to hold water in soil, or to adsorb contaminants when used in environmental applications such as wastewater treatment. However, SSA is a difficult measurement because the ability to interrogate pores of varying volumes depends strongly on the specific method utilized. The results from Control Laboratories are based on a butane activity method proposed by McLaughlin et al. (2012) and recommended as part of the International Biochar Initiative (IBI) test protocol. Comparison of the SSA data in Tables 3.1 and 3.4 to those acquired through in-house N2 adsorption measurements is discussed in Section 3.4

Table 3.2 presents soil enhancement properties of biochar derived from the same four agricultural waste biomass streams as presented in Table 3.1. Here the main nutrients of interest are organic nitrogen (org-N), phosphorous (P) and potassium (K), often referred to in aggregate as N/P/K. Some amount of nitrogen is also present as ammonia (NH_4-N) and nitrate (NO_3-N). Perhaps the most striking results from Table 3.2 are those associated with the very high N/P/K measurements for the hemp meal (HM) biochar, which at 800^{o}C processing temperature were measured as 35,162, 12,043 and 62,248 mg/kg, respectively (equivalent to parts per million, ppm). These measurements far exceed those of the biochar materials derived from the other four target

feedstocks. It is also instructive to compare the organic carbon content, H:C ratio and N/P/K values for the current hemp meal (HM) and wood pellet (WP) data to that provided by Aries Clean Technologies for their commercial-scale biochar product generated by a downdraft gasifier (Appendix A). Table 3.3 shows a comparison among the critical soil amendment properties of these different biochar materials. Also included are data for a hypothetical blend of HM/WP biochars, based on the known availability of the raw biomass feedstocks (discussed in Chapter 4) and the measured average yields provided in Table 3.1, resulting in a blend comprised of 28% hemp meal biochar and 72% woody biomass biochar. Generally, the wood pellet biochar is much higher in organic carbon content than the commercial Aries product, while the hemp meal biochar provides relatively high N/P/K concentrations, even when blended at 28%. These results illustrate that it may be possible to effectively combine biochar materials to produce a viable commercial product that commands a market price necessary to achieve economic viability at scale, as further discussed in Chapter 4.

3.2. Biochar produced by co-pyrolysis of biomass and agricultural mulch film

As discussed in Section 1 and illustrated in Figure 1.1, the underlying motivation for the present research is the investigation of co-pyrolysis of agricultural mulch films with widely available biomass waste resources from agricultural operations. The combination of relatively small amounts of plastic (25% by mass or less) with biomass in a thermochemical conversion process has been explored mainly for the objective of catalyzing and enhancing yield of liquid biofuels, not necessarily from the prospective of making value-added biochar products. The goal is to address several compelling research questions that relate directly to the sustainability and economic viability of a farm-based co-pyrolysis system: (a) how do biochar properties change when agricultural residues are co-pyrolyzed with low-density polyethylene agricultural mulch film

(AMF) material, and (b) is biochar generated from co-pyrolysis of agricultural residues and LDPE suitable for soil amendment?

Tables 3.4 and 3.5 are related to Tables 3.1 and 3.2, covering selected physical properties and soil enhancement characteristics of biochar materials produced from the same biomass waste resources, but now including either 5% or 25% by mass of LDPE mulch films. Generally, the data collected indicate that the presence of plastics at these relatively low concentrations has little to no effect on the quality of the biochar, which means it can potentially be suitable as a soil amendment to replace conventional fertilizers. Because the chemical structure of LDPE contains only carbon and hydrogen atoms [$(C_2H_4)_n$], it's not altogether surprising that biochar produced with small amounts of this material would not show elevated levels of inorganic or heavy metal contamination. However, despite this rationale, international governance organizations such as the International Biochar Initiative (IBI) specifically limit use of non-biomass feedstocks for producing biochar intended for soil applications. The requirements mandated in Europe are even more stringent; as stated in the European Biochar Certificate guidelines document (EBC, 2012) "Only plant biomasses may be used to produce biochar." and this applies whether the biochar is used for animal feed, agricultural or material applications.

Considering the results in Table 3.4, one can observe that the average total yield decreases with increasing content of LDPE, from 0 to 5 to 25 w.t%. This suggests that a relatively higher proportion of the LDPE mass is driven off in the gas phase as a pyrolysis co-product instead of being retained as solid carbon in the final biochar product. The total ash results are instructive because for either a relatively high or low ash content material (hemp meal vs. wood pellets) the

presence of LDPE had a small influence on the biochar produced by co-pyrolysis. This further supports the hypothesis that LDPE products go off in the gas phase, and also suggests that there are not significant inorganic "contaminants" contributing mass beyond the [$(C_2H_4)_n$] molecular backbone.

Other parameters such as physical properties, soil enhancement properties and chemical assessments can be affected by the variation in temperatures as observed in this study. When looking at key parameters of biochar such as organic carbon content, hydrogen-to-carbon ratio (H:C), specific surface area (SSA), total ash content, all vary across the different processing temperatures and are distinctive from the different biomass. These analyses were provided following the International Biochar Initiative guideline that demonstrates the expected different characteristics of what qualifies as biochar. Hemp meal, hammer milled boxboard and wooden pallet feedstocks that include the raw materials and the different biochar products, had very low organic carbon content based on the % of total dry mass ranging from 40 to 45%, 42 to 78% and 79 to 83%, respectively. It should be noted that the characterization was not conducted for raw wooden pallet due to shortage of feedstock material. On the other hand, wood pellets feedstocks that include raw material and the different biochar products had very high organic content ranging from 45 to 93%. This shows specifically a trend between the effect of increasing temperature and increasing organic carbon content as suggested throughout the literature (e.g., Weber and Quicker, 2018). Wood pellet biochar products [WP800C,WPFM (95/5) 800C, WPFM (75/25) 800C] showed over 90% in carbon content, suggest that the particular feedstock can be used to substitute fossil carbon carriers (Weber & Quicker, 2018).

Regarding soil amendment properties such as organic nitrogen (Org-N), phosphorus (P) and potassium (K) that are critical for plant growth, hemp meal biochar products show very high values as compared to wood pellets biochar products. HMFM (75/25) 500C has the highest organic nitrogen content (Org-N) and the highest phosphorus (P) content with 42,128 mg per kg and 16,041 mg/kg respectively. HM800C shows the potassium (K) content of up to 62,248 mg per kg. These results suggest that although hemp meal biochar products have shown some poor physical properties, they can be used as an alternative to inorganic fertilizers that can cause long term-harm to the environment and its surroundings. One option in this case could be co-pyrolyzing the hemp meal with wood pellets to create a more advantageous biochar product that meet all the physical properties guidelines but also rich in N/P/K for soil amendment application. Furthermore, the IBI standard also suggest that the presence of harmful chemicals such as arsenic, cadmium, lead, chromium, molybdenum, mercury and chlorine were not detected, suggesting that the results are below the reporting limit for each of those chemicals. This is applicable for all the primary feedstocks (hemp meal and wood pellets) biochar products and also for the hammer milled boxboard and the pallets wood feedstocks (see Appendix B).

In general, surface area increases with higher temperatures. This trend was seen when analyzing the two primary feedstocks biochar products (hemp meal and wood pellets). Wood pellet biochar product including single pyrolysis biochar product, and the two blend ratios (95:5 & 75:25) at 500 °C present the highest surface areas (207, 237 and 238 m^2/g.) However, wood pellet biochar feedstock at 800°C produced the lowest specific surface area values across all three treatments. Other parameters like specific surface area may be dependent on feedstock type and other biochar properties such as cation exchange capacity or water holding capacity. This method can present

some limitations. A large surface area composed of many very small pores may not be easily accessible to some gases such as N_2 (Weber & Quicker. 2018).

3.3. Effect of co-pyrolysis temperature on critical biochar properties

Section 3.3 explores the effect of temperature on critical biochar physical properties for pyrolysis and co-pyrolysis of wood pellets with low-density polyethylene at 500, 650 and 850°C. The value of 650°C represents the midpoint between the other selected temperatures for the study. Experiments were run at an additional temperature to better explain the functional relationship between increasing temperatures and parameters such as pH, specific surface area by butane activity, organic carbon content, organic nitrogen content, phosphorus and potassium (Figures 3.1 – 3.6). These figures are based on the data provided by Control Laboratories (Appendix B), following the International Biochar Initiative protocol as described in Chapter 2. Figure 3.1 shows a non-linear relationship between pH and increasing temperature, contrary to what was suggested by many prior researchers regarding the increase in pH with increasing temperature. The figure shows an increase from 4.4 to 7.7 at 500 and 650°C. However, the figure shows a decrease from 650°C to 5.9 at 800°C. Figure 3.2 indicates that as temperature increases, the specific surface area decreases. This is applicable to the different blend ratio (100:0, 95:5 and 75:25). According to literature, increasing temperatures increase surface area and pore volume due to increase in micropore volume (Zhao et al., 2017). This can also be explained by the method used for this analysis may not be adequate to capture all of the micropores, therefore values may be underestimated. Weber & Quicker (2018) suggested that the best method for this analysis may be by CO_2 adsorption at temperature 273 K, due to the high kinetic energy that may enable diffusion more easily into micropores. Figure 3.3 shows what is expected regarding the effect of increasing organic carbon content with increasing temperature. At higher temperature, there is a higher degree

of carbonization which explains the increase in carbon content from 500 to 800°C. It can also be suggested that the presence of mulch films has a small influence on the carbon content as the values decrease slightly with increasing blend ratio. Figure 3.4 describes a positive correlation between increasing temperatures and organic nitrogen content. Limited literature has looked closely at the effect of increasing temperatures and increasing organic nitrogen, phosphorus and potassium content. This mostly varies from feedstock to feedstock; woody biomass feedstocks have different composition than cellulosic or hemi-cellulosic biomasses. Figures 3.5 and 3.6 illustrate the effect of increasing temperature on phosphorus (P) and potassium (K) content, respectively. The presence of these essential nutrients in the biochar is important for plant growth (Rajkovich et al., 2012). As can be seen, it is difficult to capture an exact explanation for these trends, as both figures show a decrease in nutrient contents from 500 to 650 °C and an increase at 800°C. Interestingly, in the case of phosphorous, there was a consistent trend of 5% LDPE lowering biochar P content relative to the 100/0 baseline, while co-pyrolysis with 25% LPDE produced a biochar with substantially higher phosphorous concentration than the no-LDPE case. Although the overall trend in Figure 3.6 appears to be the same for all WP/LDPE ratios, the reason for the absolute changes with increasing pyrolysis temperature are not clear. According to Weber and Quicker (2018), alkali metals like potassium are partly released into the gas phase during thermochemical conversion, but the greatest release occurs either below 500^{o}C or above 800^{o}C, completely outside of the range of this study. If potassium does not leave the biomass substrate in the gas phase, it is expected that its concentration would increase monotonically with pyrolysis temperature, similar to the trend observed for organic nitrogen in Figure 3.4.

3.4. Comparative analysis of in-house and 3rd-party measurements of pH and specific surface area

In-house measurements of pH and specific surface area via nitrogen adsorption were conducted to compare to standard tests provided by Control Laboratories for hemp meal and wood pellets biochar products (Table 3.6). The pH measurements show the relationship between increasing temperatures and increase in alkalinity from 500 to 800°C. This goes in accordance what most literature reported on the effect of increasing temperature on biochar pH. On the other hand, looking at specific surface area by N_2 adsorption, there seems to be a variation in the measurements obtained. As mentioned above, similar to butane, N_2 does not diffuse well within the micropores.

Table 3.1 – Selected physical properties and empirical yield of biochar derived from pyrolysis of waste biomass materials [HM = hemp meal; WP = wood pellets; HB = hammer milled box board; PW = pallet wood]

Feedstock	Temp (°C)	Average yield (%)	Organic Carbon (% Tot DM)	Total ash (%)	Moisture content (% wet wt.)	Bulk density (kg/m^3)	H:C	Total N (%)	pH	EC (dS/m)	Specific surface area (m^2/g dry)
RAW HM	-	-	44.4	13.5	9.4	233.9	1.36	3.99	7.00	2.45	208
HM	500	33.7	45.1	34.1	4.0	192.2	0.71	4.02	12.0	4.01	178
HM	800	27.2	47.0	44.0	0.0	187.4	0.44	3.52	12.6	9.50	161
Raw WP	-	-	48.9	0.6	15.9	346.0	1.43	0.18	12.37	0.11	154
WP	500	27.6	83.1	1.4	3.0	233.9	0.56	0.40	4.40	0.11	207
WP	800	21.9	93.2	1.6	3.3	249.9	0.23	0.76	5.93	0.49	118
Raw HB	-	-	44.9	3.7	17.0	49.7	2.35	0.21	7.91	0.34	203
HB	500	28.0	69.1	2.2	5.6	126.5	0.66	0.75	7.24	0.10	205
HB	800	22.0	76.2	16.0	12.8	40.0	0.40	0.66	12.0	6.52	215
Raw PW	-	-	-	-	-	-	-	-	-	-	-
PW	500	28.0	78.7	2.2	5.6	126.5	0.66	0.75	7.24	0.10	205
PW	800	25.0	89.3	3.8	4.5	152.2	0.26	0.99	11.3	1.38	149

Note: Raw Pallet Wood (PW) was not characterized because of a lack of feedstock material. Tot DM = Total Dry Mass.

Table 3.2 - Soil enhancement properties of biochar derived from pyrolysis of waste biomass materials [HM = hemp meal; WP = wood pellets; HB = hammer milled box board; PW = pallet wood]

			NUTRIENTS (mg/kg)				
Feedstock	**Temp °C**	**Volatile matter (%/dw)**	**K**	**P**	**NH4- N**	**NO3-N**	**Org-N**
Raw HM	-	73.8	17,220	4,716	529	425	38,933
HM	500	30.9	51,432	14,468	13.8	2.2	40,168
HM	800	16.1	62,248	12,043	9.8	14	35,162
Raw WP	-	80.2	1,361	99	1.4	0.6	1,784
WP	500	20.7	2,518	69	2.6	0.6	4,040
WP	800	6.0	2,166	10	1.0	1.2	7,615
Raw HB	-	81.4	358	74	6.7	6.6	2,037
HB	500	24.6	371	184	0.6	0.7	3,659
HB	800	8.4	421	118	1.1	1.4	6,632
PW	500	20.8	2,109	220	0.5	0.3	7534
PW	800	5.5	1,510	106	3.6	0.3	9,855

Note: Raw Pallet Wood (PW) was not characterized because of a lack of feedstock material.

Table 3.3 – Comparative assessment of current hemp meal (HM) and wood pellet (WP) biochars produced at 800ºC, with hypothetical HM/WP blend and commercial Aries Green® biochar product (Appendix A)

Parameter	**Hemp meal (HM)**	**Wood pellet (WP)**	**HM/WP blend (28:72)**	**Aries Green®**
Organic carbon (%)	45.1	91.2	78.3	88.7*
H:C	0.44	0.23	0.29	0.39
Org-N (mg/kg)	35,162	7,615	15,328	10,936
P (mg/kg)	12,043	10	3,379	1,918
K (mg/kg)	62,248	2,166	18,989	3,464

*The commercially available Aries Green product packaging indicates “USDA certified 96% biobased carbon.”

Table 3.4 – Selected physical properties and empirical yield of biochar derived from co-pyrolysis of hemp meal (HM) and wood pellets (WP) with low-density polyethylene (LDPE) mulch film

Feedstock (Biomass:LDPE ratio)	**Temp (°C)**	**Average total yield (%)**	**Organic Carbon (% Tot DM)**	**Total ash (%)**	**Moisture content (% wet wt.)**	**Bulk density (kg/m^3)**	**H:C**	**Total N (%)**	**pH**	**EC (dS/m)**	**Specific surface area (m^2/g dry)**
HM (100/0) Biomass only	500	33.7	45.1	34.1	4.0	192.2	0.71	4.02	12.0	4.01	178
HMFM (95/5)	500	32.2	48.8	37.5	11.9	190.6	0.64	4.21	10.5	2.71	148
HMFM (75/25)	500	28.3	46.1	33.4	12.7	203.4	0.74	3.75	12.0	4.11	175
HM (100/0) Biomass only	800	27.2	47.0	44.0	0.0	187.4	0.44	3.52	12.6	9.50	161
HMFM (95/5)	800	28.5	43.6	40.5	12.9	206.6	0.56	3.38	12.4	6.44	164
HMFM (75/25)	800	22.3	50.0	41.9	12.4	198.6	0.40	3.58	12.5	7.61	173
WP (100/0) Biomass only	500	27.6	83.1	1.4	3.0	233.9	0.56	0.40	4.40	0.11	207
WPFM (95/5)	500	23.4	83.0	1.9	3.8	213.0	0.52	0.39	11.1	0.12	237
WPFM (75/25)	500	20.7	81.1	3.2	3.5	289.9	0.54	0.36	10.5	0.14	238
WP (100/0) Biomass only	800	21.9	93.2	1.6	3.3	249.9	0.23	0.76	5.93	0.49	118
WPFM (95/5)	800	20.6	92.3	2.3	4.1	233.9	0.23	0.74	11.1	0.52	133
WPFM (75/25)	800	18.6	91.0	3.6	3.1	262.7	0.24	0.74	8.04	1.09	131

Table 3.5 – Soil enhancement properties of biochar derived from co-pyrolysis of hemp meal (HM) and wood pellets (WP) with low-density polyethylene (LDPE) mulch film

			NUTRIENTS (mg/kg)				
Feedstock	**Temp °C**	**Volatile Mater (%/dw)**	**K**	**P**	**NH4- N**	**NO3-N**	**Org-N**
HM (100/0) Biomass only	500	30.9	51,432	14,468	13.8	2.2	40,168
HMFM (95/5)	500	30.9	45,402	11,931	23.7	2.2	37,465
HMFM (75/25)	500	27.6	58,721	16,041	2.9	2.5	42,128
HM (100/0) Biomass only	800	16.1	62,248	12,043	9.8	14	35,162
HMFM (95/5)	800	16.2	53,759	10,569	11.5	100	35,654
HMFM (75/25)	800	21.1	61,407	11,154	9.7	36	33,799
WP (100/0) Biomass only	500	20.7	2,518	69	2.6	0.6	4,040
WPFM (95/5)	500	17.7	2,252	40	0.4	0.4	3,933
WPFM (75/25)	500	18.3	2,413	82	0.3	0.3	3,631
WM (100/0) Biomass only	800	6.0	2,166	10	1.0	1.2	7,615
WPFM (95/5)	800	3.0	1,816	2	0.2	0.0	7,383
WPFM (75/25)	800	3.8	1,675	24	0.3	0.3	7,370

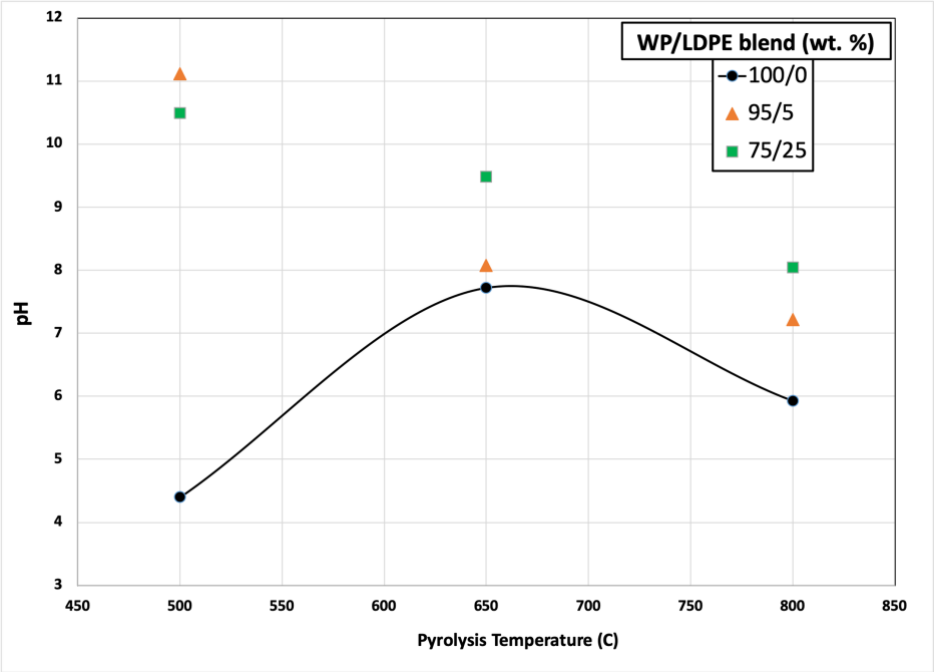

Figure 3.1 – Effect of co-pyrolysis temperature on pH for wood pellet (WP) feedstock with different LDPE blend ratios

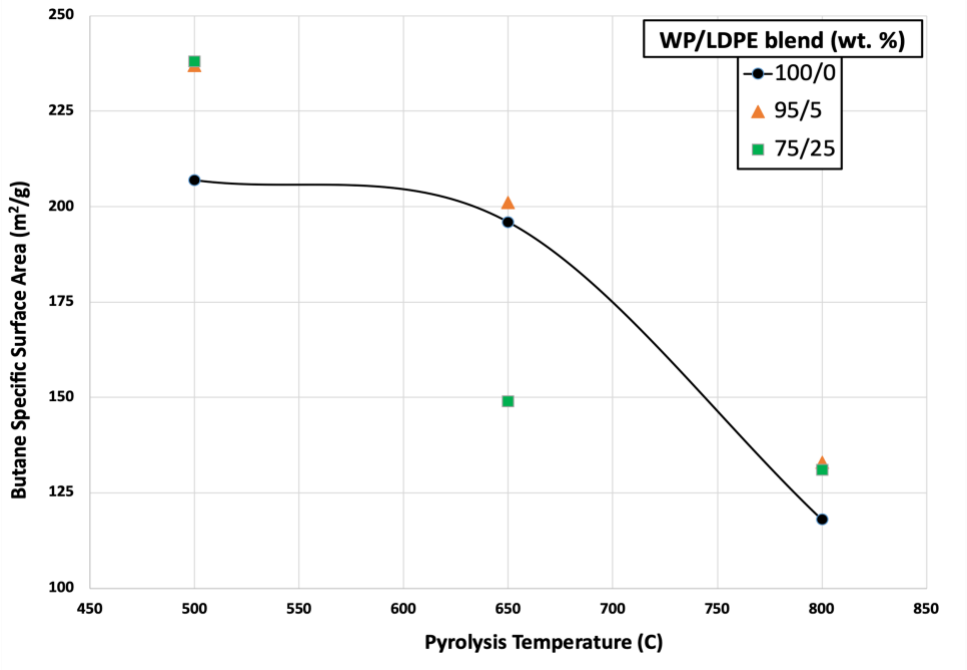

Figure 3.2 – Effect of co-pyrolysis temperature on specific surface area (m^2/g) by butane activity for wood pellet (WP) feedstock with different LDPE blend ratios

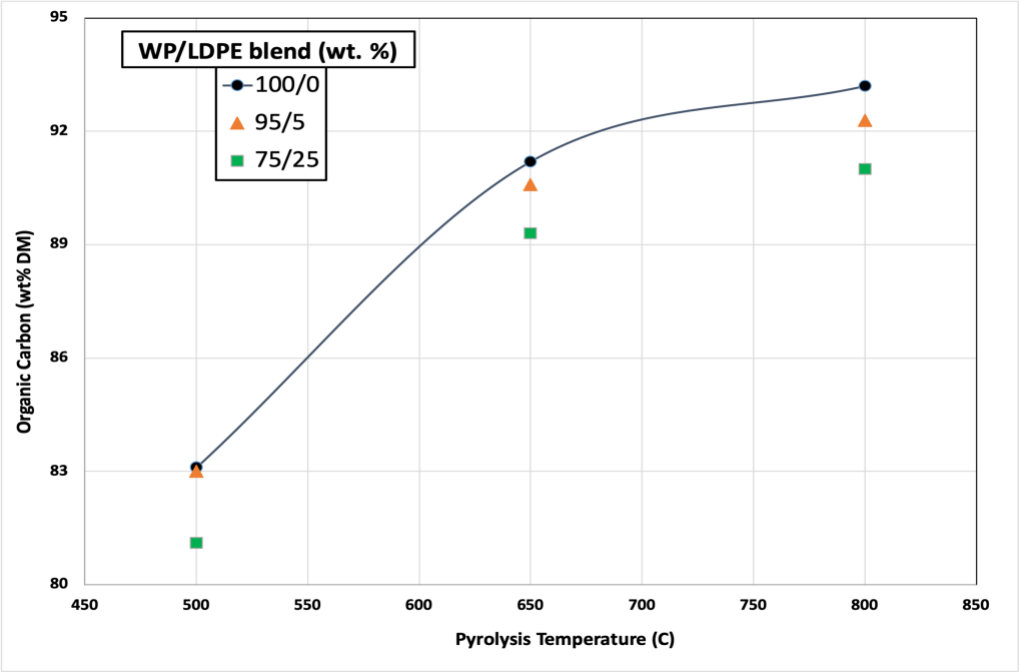

Figure 3.3 – Effect of co-pyrolysis temperature on organic carbon content (wt% DM) for wood pellet (WP) feedstock with different LDPE blend ratios

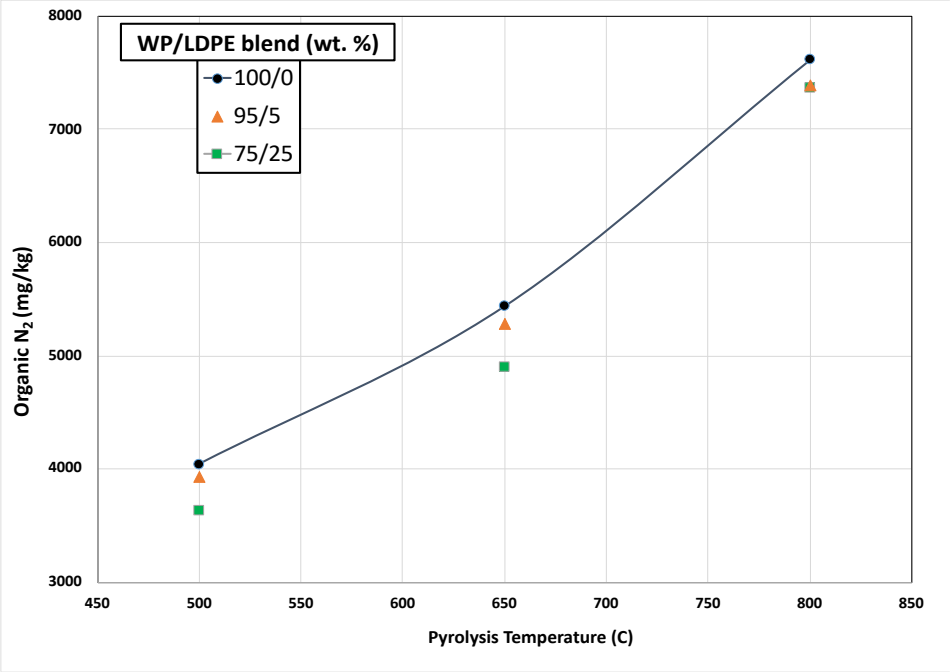

Figure 3.4 – Effect of co-pyrolysis temperature on organic nitrogen content (mg/kg) for wood pellet (WP) feedstock with different LDPE blend ratios

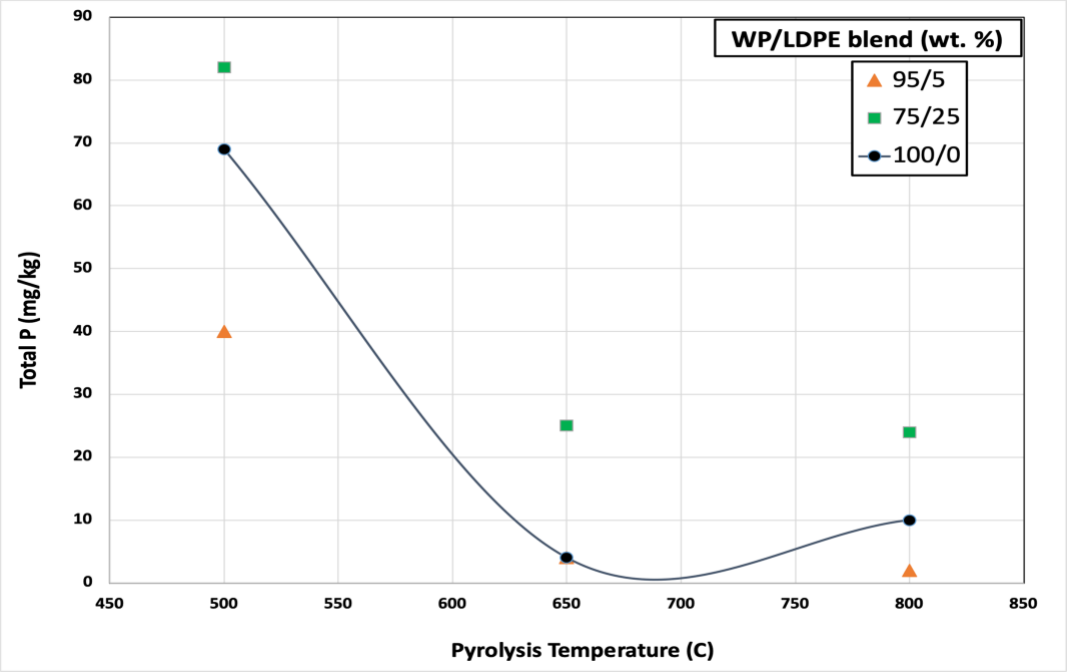

Figure 3.5 – Effect of co-pyrolysis temperature on total phosphorus content (mg/kg) for wood pellet feedstock with different LDPE blend ratios

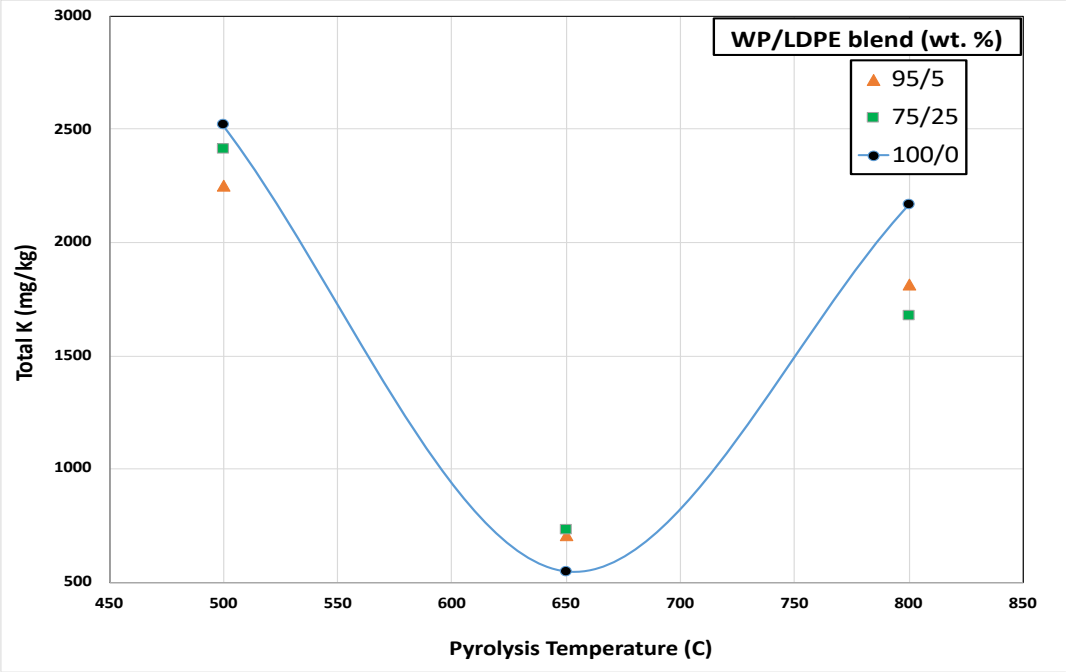

Figure 3.6 – Effect of co-pyrolysis temperature on total potassium content (mg/kg) for wood pellet (WP) feedstock with different LDPE blend ratios

Table 3.6 – Comparison of measurements for pH and specific surface area via nitrogen adsorption and butane adsorption for hemp meal and wood pellets biochar products.

		METHODS			
		In-house		Control Laboratories	
Feedstock	Temperature (°C)	EC pH	SSA via N_2 adsorption (m^2/g)	EC pH	SSA via butane activity (m^2/g)
HM	500	11.4	3.6	12.0	178
HM	800	12.0	6.0	12.6	161
HMFM (95/5)	500	11.3	3.2	10.5	148
HMFM (95/5)	800	12.0	5.6	12.4	164
HMFM (75/25)	500	11.5	6.9	12.0	175
HMFM (75/25)	800	12.0	10.8	12.0	173
WP	500	8.3	52.7	4.4	207
WP	650	8.5	196.7	7.7	196
WP	800	10.4	102.9	5.9	118
WPFM (95/5)	500	8.0	19.4	11.1	237
WPFM (95/5)	650	8.3	136.4	8.1	201
WPFM (95/5)	800	10.3	198.9	7.2	133
WPFM (75/25)	500	8.3	31.1	10.5	238
WPFM (75/25)	650	8.5	83.0	9.5	149
WPFM (75/25)	800	12	14.1	8.0	131
HB	500	9.4	-	9.0	215
HB	800	11.7	-	12.0	215
PW	500	7.3	25.3	7.24	205
PW	800	8.9	112.8	11.3	149

Note: Surface area measurements via nitrogen adsorption of hammer milled boxboard biochar (HB) was not conducted due to lack of biochar materials.

CHAPTER 4

CARBON SEQUESTRATION AND TECHNO-ECONOMIC ANALYSIS OF FARM-BASED CO-PYROLYSIS SYSTEM

4.1 Introduction

The previous chapters presented a comprehensive literature review of biochar derived from pyrolysis and co-pyrolysis of organic wastes with different plastics including low-density polyethylene mulch films, in-house production and measurements of biochar produced from four different agricultural feedstocks with varying amounts of LDPE, and extensive biochar characterization following an International Biochar Initiative (IBI) standard testing protocol. The results presented in Chapter 3 clearly demonstrate the technical viability of pyrolysis and co-pyrolysis processes to produce high-quality biochar. However, to fully assess the sustainability of these processes, it is also important to understand the carbon sequestration potential of a farm-based co-pyrolysis system, as well as the economic viability at scale for farms in the western New York region. Thermochemical conversion has the potential to sequester carbon on a large scale, based on prior studies focused on New York (Roberts et al., 2010), California (Breunig et al., 2019) , China (Feng et al., 2020) and elsewhere. In this research program, we have sought to assess its suitability at the scale of a single farm or a regional cooperative of farms, whereby agricultural waste from multiple locations is processed at a centralized conversion facility.

As the basic science behind pyrolysis and most thermochemical conversion processes is well understood, attention has recently shifted toward engineering and deploying commercial-scale systems, including both mobile and stationary platforms. There are several existing commercial

systems designed for relatively small feed flow rates that may be suitable for the single farm or regional processing system design:

- ***Charboss***

  Charboss technology is a mobile machine that produces biochar suitable for the restoration of degraded soil. It has a fewer size and moisture content limitations than existing mobile biochar technologies (US Forest Service, 2020).

- ***Pyrotech***

  Pyrotech technology converts biomass into renewable fuels and biochemicals. The technology favors production of bio-oil and syngas from waste wood and agriculture residues that can be used locally or at another facility (Pyrotech Energy, 2020).

- ***Biogreen***

  Other technologies such as Biogreen technology also involve mobile or containerized pyrolysis plants (Biogreen, 2021). This system offers many advantages that include quick installation, facilitated transport and long-term storage. However, the technology can only work in limited space areas and process a limited amount of waste at a time, which can offset the benefits of the biochar products generated and limit its applications.

This analysis will assess the carbon sequestration potential of a farm-based pyrolysis system that can process both agricultural solid wastes and low-density polyethylene mulch films. This model will be based on Biomass Controls' Biogenic Refinery (Figure 4.1), a system that was initially designed to treat human wastes in areas that lack centralized wastewater treatment infrastructure, by producing hydrogen rich syngas and solid biochar that can be used for various applications. Because RIT owns a Biomass Controls system is that RIT owns a system, and it has already been

utilized in prior research (e.g., Rodriguez Alberto et al., 2019), its performance and associated operation and maintenance costs are well understood.

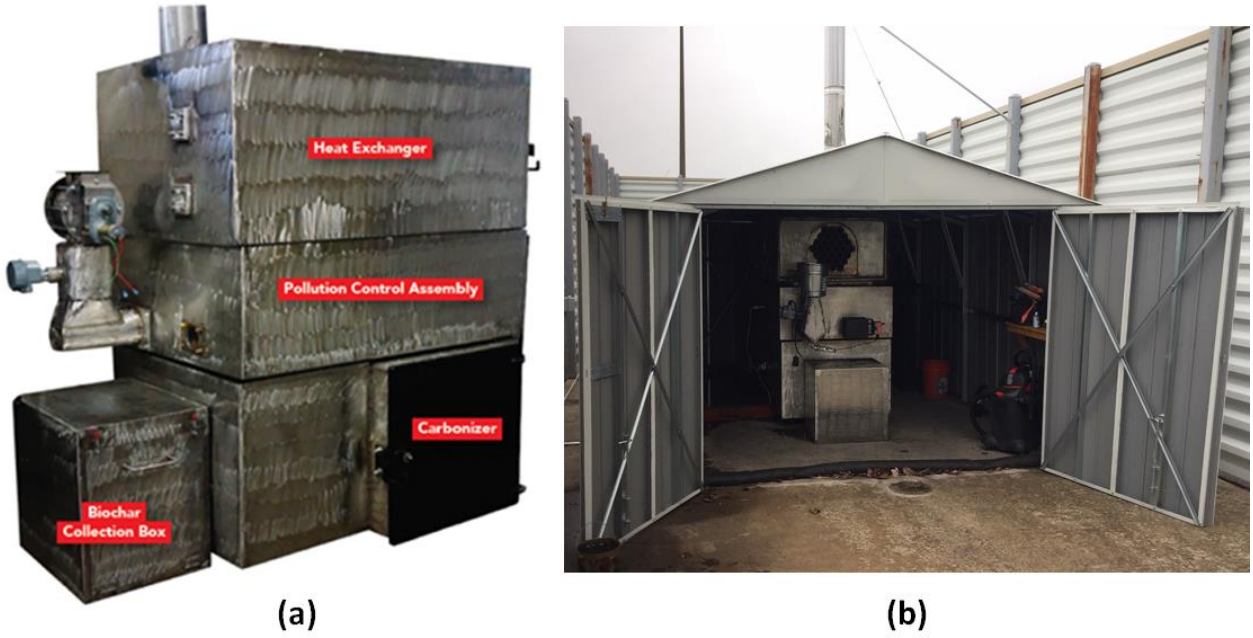

Figure 4.1 - Biogenic Refinery system manufactured by Biomass Controls PBC (Putnam, CT) (b) Primary system components; (b) System located at Rochester Institute of Technology.

4.2 System model description and assumptions

The first part of our sustainability analysis followed the methodology of Feng et al. (2020) for the carbon sequestration potential of biochar from agricultural wastes in China. We applied a similar analysis framework for the western New York region using a single farm located in western New York (hereafter referred to as "Farm A") as a model case study. Farm A was selected because they are a committed partner in the broader project funded by the Foundation for Food and Agriculture Research (Figure 1.1), and willing to share data regarding volumes of organic and agricultural mulch film wastes, and their associated disposal costs. Both carbon sequestration and techno-economic analyses (Section 4.4) explored different case scenarios. The first scenario involved a single pyrolysis system processing wastes generated at only one farm location, using Farm A as

representative of the types and amounts of these wastes (Table 4.1). The second scenario expanded the initial analysis to a regional model covering multiple farms in close proximity that generate 10 times the waste of the single-farm scenario. In this scenario, it was assumed that all 10 farms produce the same quantity of feedstocks and transport these feedstocks to Farm A for processing. As illustrated in Figure 4.2, more than 10 farms exist within a 10 km straight-line distance from Farm A.

Figure 4.2 – Farms within 5, 10 and 25 km radii from Farm A in the region west of Rochester, NY on the southern shore of Lake Ontario (original image extracted from Google Maps)

The two baseline pyrolysis scenarios (single farm and regional) were further extended to consider the impact of co-pyrolyzing the feedstocks with low-density polyethylene mulch films at different blend ratios of 95:5 and 75:25. To be conservative in the computation of carbon sequestration and

economic potential, it was assumed that biochar generated by co-pyrolysis (biomass + LDPE) is not used as a soil amendment, and thus cannot be sold to generate revenue. It was therefore necessary to determine the number of days per year that LDPE mulch films would be co-processed with biomass wastes, which, based on the data in Table 4.1, indicates a total biomass generation rate of 255.6 t/year. Because it was assumed that biochar produced by co-pyrolysis cannot be sold or used for soil amendment, the further assumption was made that co-pyrolysis will be conducted at a 75:25 biomass-to-LDPE ratio to complete the mulch film processing in as few days as possible. If the system operates at 80% utilization (Roberts et al., 2010), then 0.9 t of biomass would be processed daily. At a 75:25 ratio, co-pyrolysis operation would blend in 0.291 t of mulch film, and it would take about 4 days to process the entire 1.2 t used annually.

Carbon sequestration model calculations (Section 4.3) were generated for three different processing temperatures to match the experimental data at 500, 650 and 800°C. To estimate the biochar yield from the system, the sum of the weighted averages of all the biomass and their respective yields were taken. The goal was to compare which processing temperatures would be more beneficial in terms of net carbon sequestration potential, as well as to determine the impact factor of the biochar for every ton of biochar produced. From these results, the temperature yielding the highest carbon sequestration potential was then used as the basis for the techno-economic model presented in Section 4.4.

Table 4.1: Representative agricultural wastes generated by Farm A

Feedstock type	Annual amount generated (t)	Comments
Crop residues	61.2	Mostly from corn, tomatoes and peppers. Standard practice is to till into the soil at the end of the growing season.
Woody biomass	193.5	Primarily comprised of apple tree trimmings.
Cardboard boxes	0.45	
Wooden pallets	0.45	
LDPE mulch films	1.2	Amount estimated from total 8 acres of crops using mulch films, coupled with typical areal density provided by *http://www.trellishorticulture.com/plastic-mulch-films.php*

4.3 Carbon sequestration analysis

The carbon sequestration analysis focused on determining the greenhouse gases mitigation potential of farm-based pyrolysis systems, according to different scenarios: single farm pyrolysis, regional farm pyrolysis, single farm co-pyrolysis and regional farm co-pyrolysis. These analyses were based upon model input parameters and assumptions derived from both in-house empirical results and data provided by key literature sources of Roberts et al. (2010) and Feng et al. (2020), as summarized in Tables 4.2 and 4.3. The ultimate goal of these analyses was to determine and compare the greenhouse gas mitigation potential across the entire range of pyrolysis conversion temperatures, but also across the different scenarios for the farm-based pyrolysis system.

In this analysis, with wood pellets accounting for the majority of the waste feedstocks available at the farms, the total available feedstock for the single pyrolysis and co-pyrolysis was 255.6 tons. This includes all feedstock types generated at the farm as described in Table 4.1. At the regional level, certain assumptions were made to estimate the wastes generated at the surroundings farms (Figure 4.2) and transported to the centralized location for conversion via pyrolysis. It was assumed that in the regional scenario, the available waste feedstocks will be 10 times of that generated on a single farm (more than 10 farms located within 10 km radius); Figure 4.2. Therefore, the total available feedstocks for the regional pyrolysis and co-pyrolysis scenarios were 2,556 tons. It is understood that the quantity of wastes among all the different farms would vary, therefore they are only applicable for this case study. It was also assumed that all of these available feedstocks would be fully converted into biochar at empirically determined yields from wood pellets at 500, 650 and 800^{o}C.

Table 4.2 - Carbon sequestration analysis model input parameters and assumptions for a single farm pyrolysis system. This analysis generally follows the framework of Feng et al. (2020) on potential biochar sequestration for agricultural wastes in China.

Item	Parameter	500ºC	650ºC	800ºC	Sources/comments
Biochar production and soil storage	Total Feedstock (t)	255.6	255.6	255.6	Farm A data (Table 4.1)
	Transportation loss (%)	0	0	0	No transportation losses because biochar is moved entirely within a single farm.
	Biochar yield (%)	29.1	25.5	23.2	In-house empirical data
	Biochar moisture content (%)	3.3	2.9	2.5	Control Laboratories analysis (Appendix B)
	Biochar carbon content (%)	73.9	78.0	82.1	Control Laboratories analysis (Appendix B)
	Biochar stability factor	73.1			Value for firewood (FR) from Feng et al. (2020). This is a conservative value relative to the 80% proposed by Roberts et al. (2010).
	C-CO_{2e} conversion factor	3.67			Feng et al. (2020)
Agricultural production benefits	Biochar application rate (t hm^{-2})	10			Feng et al. (2020)
	Increase in crop biomass output (%)	10			Roberts et al. (2010)
	Crop biomass yield (t hm^{-2})	13.36			Roberts et al. (2010)
	C content in crops (%)	45			Roberts et al. (2010)
	Agricultural fertilizer application (N/P/K) (kg hm^{-2})	191.7 51.9 21.8			Feng et al. (2020), from dissertation of Yan (2008)
	Agricultural fertilizer reduction (N/P/K)	10 5			Feng et al. (2020), from dissertation of

	(%)	5	Li (2015)
	CO_{2e} emissions from N/P/K production (kg)	3.0 0.7 1.0	Roberts et al. (2010)
Suppression of N_2O emissions	N_2O emissions (kg hm^{-2})	2.36	Feng et al. (2020)
	N_2O emissions suppression rate (%)	60	Feng et al. (2020)
Impact on soil organic content (SOC)	Initial value of SOC content (t hm^{-2})	42	Feng et al. (2020)
	SOC increase ratio (%)	10	Feng et al. (2020)
Pyrolysis plant production	Unit energy consumption (MJ t^{-1})	23.96	Feng et al. (2020)
	Unit raw material discharge (kg t^{-1})	3.6	Feng et al. (2020)

Note: Unlike the regional pyrolysis scenario (Table 4.3), greenhouse gas emissions from biochar production and application are assumed negligible, because feedstocks and biochar products are transported only at the scale of a single farm. Avoided landfill emissions was neglected because farm-based wastes (other than LDPE mulch films) are normally not treated with this method.

Table 4.3 - Carbon sequestration analysis model input parameters and assumptions for a regional pyrolysis system. This analysis generally follows the framework of Feng et al. (2020) on potential biochar sequestration for agricultural wastes in China.

Item	Parameter	500ºC	650ºC	800ºC	Sources/comments
Biochar production and soil storage	Total Feedstock (t)	2556	2556	2556	Farm A data (Table 4.1)
	Transportation loss (%)	0	0	0	No transportation losses because biochar is moved entirely within a single farm, and material in excess of what's used at the central farm is offered for sale on-site.
	Biochar yield (%)	29.1	25.5	23.2	In-house empirical data
	Biochar moisture content (%)	3.3	2.9	2.5	Control Laboratories analysis (Appendix B)

	Biochar carbon content (%)	73.9	78.0	82.1	Control Laboratories analysis (Appendix B)
	Biochar stability factor	73.1			Value for firewood (FR) from Feng et al. (2020). This is a conservative value relative to the 80% proposed by Roberts et al. (2010).
	C-CO_{2e} conversion factor	3.67			Feng et al. (2020)
Agricultural production benefits	Biochar application rate (t hm^{-2})	10			Feng et al. (2020)
	Increase in crop biomass output (%)	10			Roberts et al. (2010)
	Crop biomass yield (t hm^{-2})	13.36			Roberts et al. (2010)
	C content in crops (%)	45			Roberts et al. (2010)
	Agricultural fertilizer application (N/P/K) (kg hm^{-2})	191.7 51.9 21.8			Feng et al. (2020), from dissertation of Yan (2008)
	Agricultural fertilizer reduction (N/P/K) (%)	10 5 5			Feng et al. (2020), from dissertation of Li (2015)
	CO_{2e} emissions from N/P/K production (kg)	3.0 0.7 1.0			Roberts et al. (2010)
Suppression of N_2O emissions	N_2O emissions (kg hm^{-2})	2.36			Feng et al. (2020)
	N_2O emissions suppression rate (%)	60			Feng et al. (2020)
Impact on soil organic content (SOC)	Initial value of SOC content (t hm^{-2})	42			Feng et al. (2020)
	SOC increase ratio (%)	10			Feng et al. (2020)
Greenhouse gas emissions during biochar production and application	Energy consumption during raw material collection (MJ t^{-1})	803			Feng et al. (2020)
	CO_{2e} emissions during collection	57			Feng et al. (2020)

	(kg t^{-1})		
	Energy consumption per unit of raw material transportation (MJ t^{-1})	49.56	Feng et al. (2020)
	Diesel calorific value (MJ kg^{-1})	44	Feng et al. (2020)
	Unit energy consumption of biochar application (MJ t^{-1})	566	Feng et al. (2020)
	Unit emissions from biochar application (kg CO_{2e} t^{-1})	45.32	Feng et al. (2020)
Pyrolysis plant production	Unit energy consumption (MJ t^{-1})	23.96	Feng et al. (2020)
	Unit raw material discharge (kg t^{-1})	3.6	Feng et al. (2020)

Note: Neglected avoided landfill emissions because farm-based wastes (other than LDPE mulch films) are normally not treated with this method.

Based on the input parameters and assumptions summarized in Tables 4.2 and 4.3, the associated carbon sequestration computations were conducted as outlined in Table 4.4 and 4.5, respectively. According to the analysis, in combination with data provided by Feng et al. (2020) with the different biomass resource types for Farm A, with hardwood trimmings accounting for the majority of the feedstock available on site, processing the wastes feedstocks at all the different temperatures have some important net greenhouse gas sequestration potential, quantified as metric tonnes (t) carbon dioxide equivalent (CO_{2e}).

The single farm pyrolysis scenario entails only the feedstocks available at the centralized farm that are processed and fully converted to biochar. For this particular scenario, the analysis results show that processing at the lowest temperature of 500^{o}C resulted in a higher CO_{2e} sequestration potential

of 192.8 t, as compared to 174.0 t and 164.3 t at 650 and 800°C, respectively. The apparent advantage of converting biomass wastes at lower temperature derives from the higher yield (29.1, 25.5 and 23.2%, for 500, 650 and 800°C, respectively), which outweighs the relatively lower biochar carbon content at lower temperature (73.9, 78.0 and 82.1%, respectively). To determine the net carbon sequestration potential, one needs to account for factors such as greenhouse gases emitted during biochar production that include emissions from pyrolysis plant construction, determined to be 0.92 t for all conversion temperatures. Again, it is important to note that in the single farm scenario, feedstock and biochar handling/transport emissions are assumed to be negligible because these materials are only moved over short distances using existing farm equipment and labor. The net greenhouse gas mitigation potential after accounting for emissions associated with plant construction is 191.8, 173.1 and 163.4 tonnes for pyrolysis at 500, 650 and 800°C, respectively (Figure 4.3). However, when looking at the values of CO_{2e} sequestered per tonne of biochar produced, the trend is that the impact factor increases as the pyrolysis temperature increases: 2.56, 2.65 and 2.75 t CO_{2e}/t biochar, respectively (Figure 4.4). These values are consistent with the lower end of the range reported by Roberts et al. (2010), but in their analysis the additional benefit of fossil energy displacement was included. Our model is based on the Biomass Controls system (Figure 4.1) that generates biochar as the primary valorized co-product, whereas many other commercial systems also produce hydrogen-rich syngas and/or bio-oil, albeit at the expense of lower biochar yield. Further comparative assessment of the present results in the context of prior published studies is provided in Section 4.5.

The regional farm scenario involves a hypothetical cooperative arrangement of farms in close proximity to Farm A that transport their waste feedstocks to the centralized pyrolysis facility

located at Farm A for processing (Figure 4.2). In this analysis, there is an additional term in the agricultural production benefits of Table 4.5, because there is excess biochar available for sale by Farm A after biochar has been applied to all of the land area available on-site (12.1 hm^2). Only the feedstocks available at each farm are processed separately. To find the total mitigation potential (t CO_{2e}), factors such as biochar production and soil storage, agricultural production benefits, and suppression of N_2O and CH_4 emissions were taken into account. The total mitigation potential was computed to be 1762.8, 1622.6 and 1538.9 t CO_{2e} at 500, 650 and 800ºC, respectively (Figure 4.5). Similar to the single farm scenario, processing feedstocks at lower temperature increases total mitigation potential due to higher solid biochar yield compared to other temperatures. The analysis shows also that when including factors such as emissions during biochar production and application, the impact factor (t CO_{2e}/t biochar) increases by about 10% as pyrolysis temperature is raised from 500 to 800ºC, even though the total mitigation impact is reduced. Combining the analyses in Tables 4.5 and 4.6 indicates that having a centralized farm that processes feedstocks at lower temperature can have significant impact on greenhouse gas mitigation potential and an important impact factor of tons of CO_{2e} sequestered per unit tonne of biochar produced from the feedstock. It is important to emphasize that the total net carbon sequestration potential of the regional pyrolysis scenario is greater as a result of the 10X higher quantity of biomass converted to biochar, but the impact factor (t CO_{2e} sequestered /t biochar) is higher in the single farm scenario because of the absence of collection and transport related emissions. The impact factor in the regional case scenario for 500, 650 and 800ºC were: 2.29, 2.4 and 2.51 t CO_{2e}/t biochar, respectively (Figure 4.6).

Regardless of the greenhouse gas mitigation potential and impact factors, processing the wastes at the three different temperatures and also with different blend ratio of agricultural mulch films can have important emissions reduction potential. In the co-pyrolysis scenarios for both single farm and regional farm models, it was found that when processing biomass feedstocks with mulch films at the different blend ratios (95:5 & 75:25), there is still important greenhouse gas mitigation potential. The experimental results obtained from Control Laboratories suggested that the blending of the mulch films at a small fraction with solid waste biomass have little to no effects on the quality of the biochar. In this study, it was determined that biochar yield and organic carbon content dominate carbon sequestration potential as seen in Figures 4.7 and 4.8. If this system is applied at a commercial scale, more research needs to be done regarding the presence of dioxins or other toxicants in the biochar before soil amendment applications. Even if it is determined that the biochar derived from co-pyrolysis would not be suitable for soil amendment and the product is discarded via landfilling or applying to non-food producing land, the biochar will still serve to sequester a large amount of carbon for many years. The carbon sequestration analysis offered important insights into the benefits of retrieving biochar from the co-pyrolysis system. Most published journal articles on co-pyrolysis of solid waste with plastics focus on bio-oil and syngas recovery for energy production. This study offers another perspective of the benefits producing biochar not just through pyrolysis but also co-pyrolysis. If developed at larger scales, this could offer a breakthrough toward the fight on climate change and enhance the concept of circular economy at both local and regional levels to the benefit of all.

Table 4.4 – Results of carbon sequestration analysis for single farm-based pyrolysis system

Data Category	Parameter	500 °C	650 °C	800°C
Biochar production and soil storage	Biochar production (t)	74.9	65.3	59.2
	Biochar applied to farm fields (t)	74.9	65.3	59.2
	Soil carbon storage	40.5	37.2	35.5
	Soil CO_{2e} storage (t)	148.6	136.7	130.5
Agricultural production benefits	Land area treated with biochar (hm^2)	7.5	6.5	5.9
	Increased crop biomass output (t)	10.0	8.7	7.9
	Plant fixed CO_{2e} (t)	17.9	14.4	13.1
	Fertilizer reduction and avoided CO_{2e} (t)	0.1	0.1	0.1
Suppression of N_2O and CH_4 emissions	N_2O emissions reduction (t)	0.0	0.0	0.0
	N_2O relief (CO_{2e}) (t)	3.2	2.8	2.5
	SOC increase (t)	31.5	27.4	24.9
	Greenhouse gas mitigation (CO_{2e}) (t)	23.1	20.1	18.2
Total mitigation potential (CO_{2e}) (t)		192.8	174.0	164.3
	Emissions during raw material collection (CO_{2e}) (t)	0.0	0.0	0.0

GHG emissions during biochar production and application	CO_{2e} emissions from transportation of raw materials and biochar (t)	0.0	0.0	0.0
	CO_{2e} emissions from dissemination of biochar (t)	0.0	0.0	0.0
	Emissions from pyrolysis plant construction (t)	0.92	0.92	0.92
Total emissions (CO_{2e}) (t)		0.92	0.92	0.92
Net greenhouse gas mitigation potential (CO_{2e}) (t)		**191.8**	**173.1**	**163.4**
Impact factor (t CO_{2e}/t biochar)		**2.56**	**2.65**	**2.76**

Table 4.5 – Results of carbon sequestration analysis for regional farm-based pyrolysis system

		Pyrolysis Temperature		
Data Category	**Parameter**	**500 °C**	**650 °C**	**800°C**
Biochar production and soil storage	Biochar production (t)	742.7	653.0	592.3
	Biochar applied to farm fields (t)	742.7	653.0	592.3
	Soil carbon storage	401.5	372.4	355.5
	Soil CO_{2e} storage (t)	1473.4	1366.8	1304.5
Agricultural production benefits	Maximum area for land application (hm^2)	74.3	65.3	59.2
	Maximum area available at Farm A (hm^2)	12.1	12.1	12.1
	Excess biochar available for sale (t)	621.3	531.6	470.9
	Increased crop biomass output (t)	16.2	16.2	16.2
	Plant fixed CO_{2e} (t)	28.9	26.8	26.8
	Fertilizer reduction and avoided CO_{2e} (t)	0.3	0.3	0.1
Suppression of N_2O and CH_4 emissions	N_2O emissions reduction (t)	0.1	0.1	0.1
	N_2O relief (CO_{2e}) (t)	31.3	27.6	25.0
	SOC increase (t)	311.9	274.3	248.8

	Greenhouse gas mitigation (CO_{2e}) (t)	228.8	201.1	182.4
Total mitigation potential (CO_{2e}) (t)		1762.8	1622.6	1538.9
GHG emissions during biochar production and application	Emissions during raw material collection (CO_{2e}) (t)	14.6	14.6	14.6
	CO_{2e} emissions from transportation of raw materials and biochar (t)	4.0	3.7	3.4
	CO_{2e} emissions from dissemination of biochar (t)	33.7	29.6	26.8
	Emissions from pyrolysis plant construction (t)	9.2	9.2	9.2
Total emissions (CO_{2e}) (t)		61.4	57.0	54.0
Net greenhouse gas mitigation potential (CO_{2e}) (t)		**1701.3**	**1565.6**	**1484.8**
Impact factor (t CO_{2e}/t biochar)		**2.29**	**2.40**	**2.51**

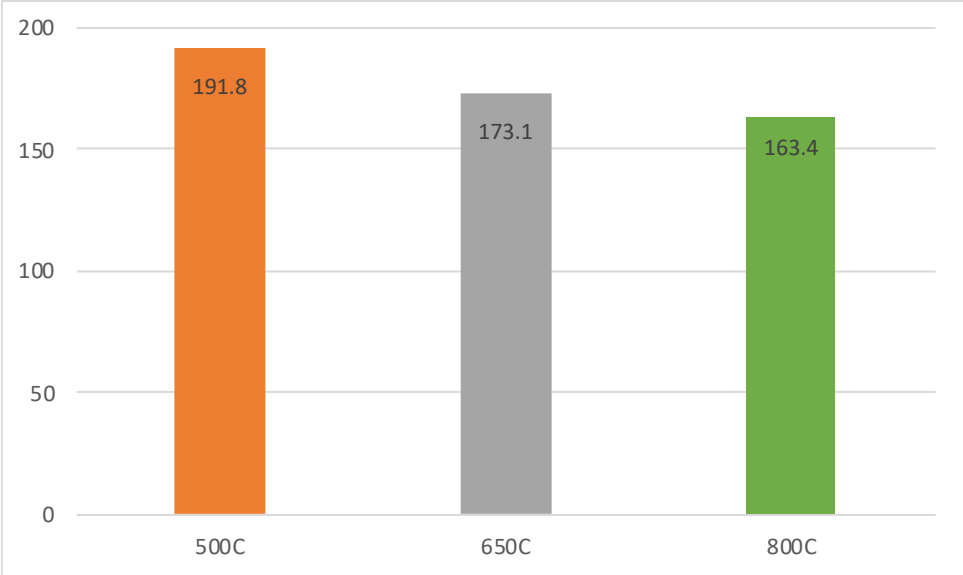

Figure 4.3 – Total carbon mitigation (t CO_{2e}) for three pyrolysis temperatures in single farm scenario.

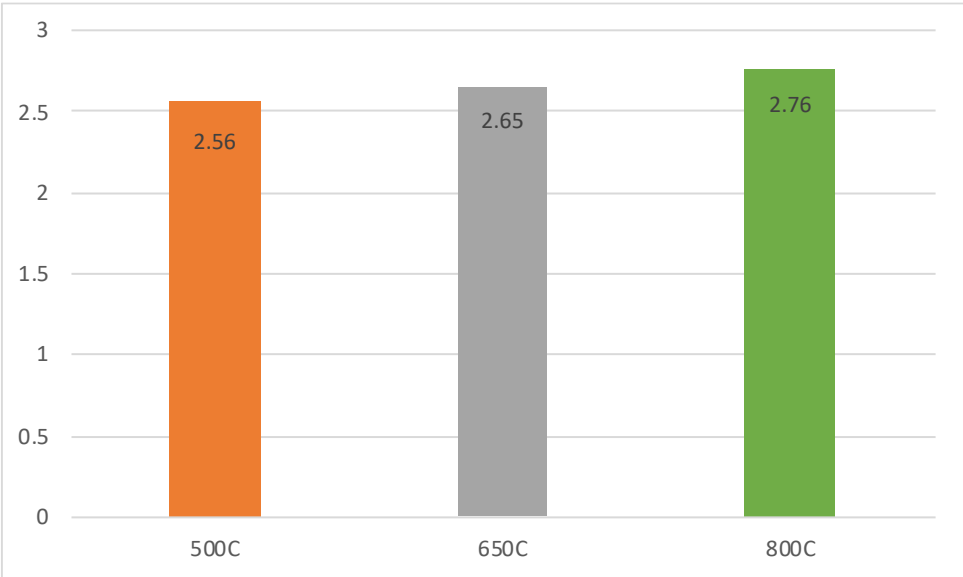

Figure 4.4 – Carbon mitigation impact factor (t CO_{2e}/t biochar) for three pyrolysis temperatures in single farm scenario.

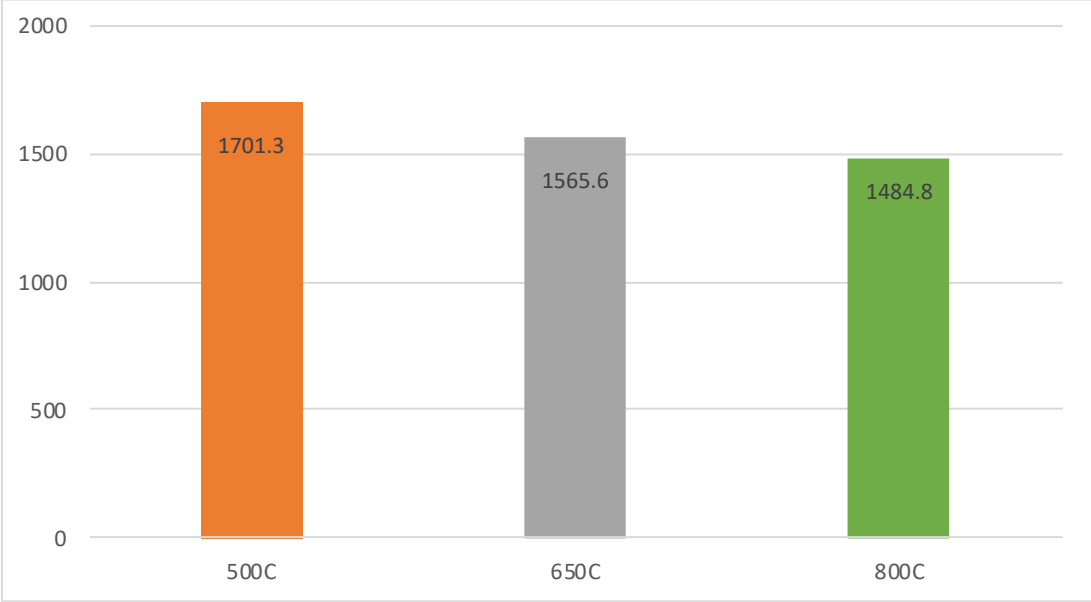

Figure 4.5 – Total carbon mitigation (t CO_{2e}) for three pyrolysis temperatures in regional farms scenario.

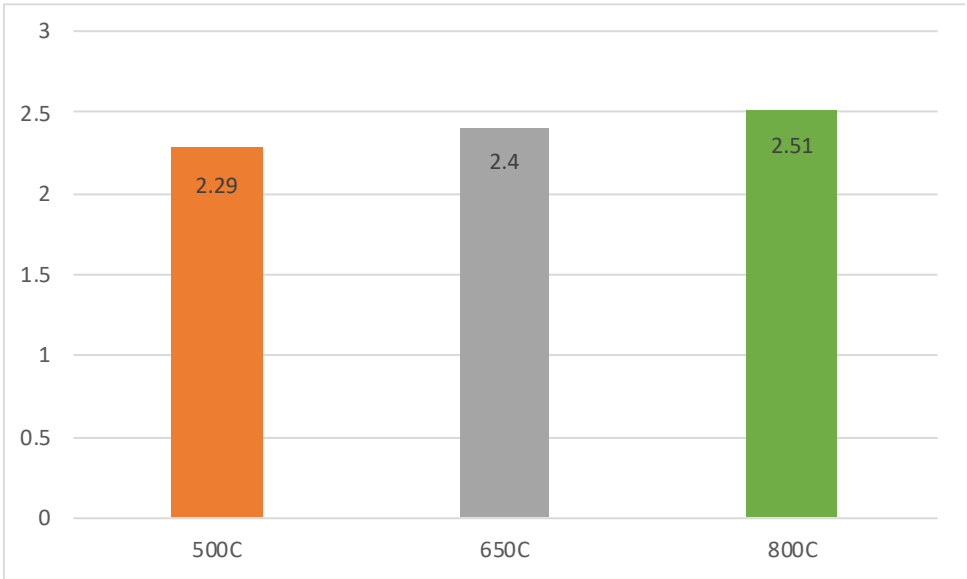

Figure 4.6 – Carbon mitigation impact factor (t CO_{2e}/t biochar) for three pyrolysis temperatures in regional farms scenario.

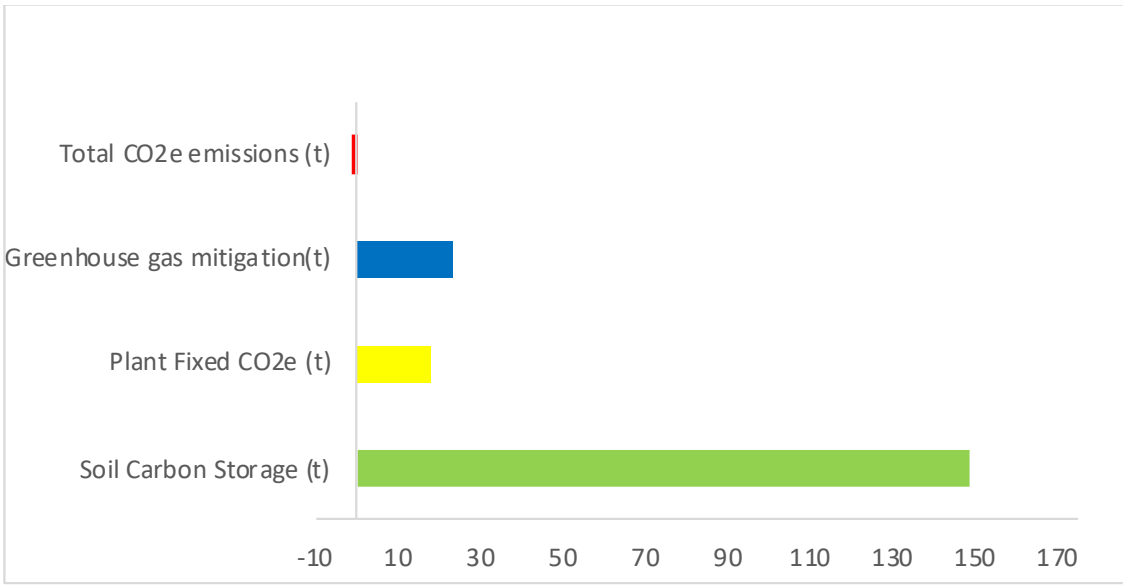

Figure 4.7 - Carbon sequestration potential and emission reduction for the single farm pyrolysis system at 500°C operating temperature

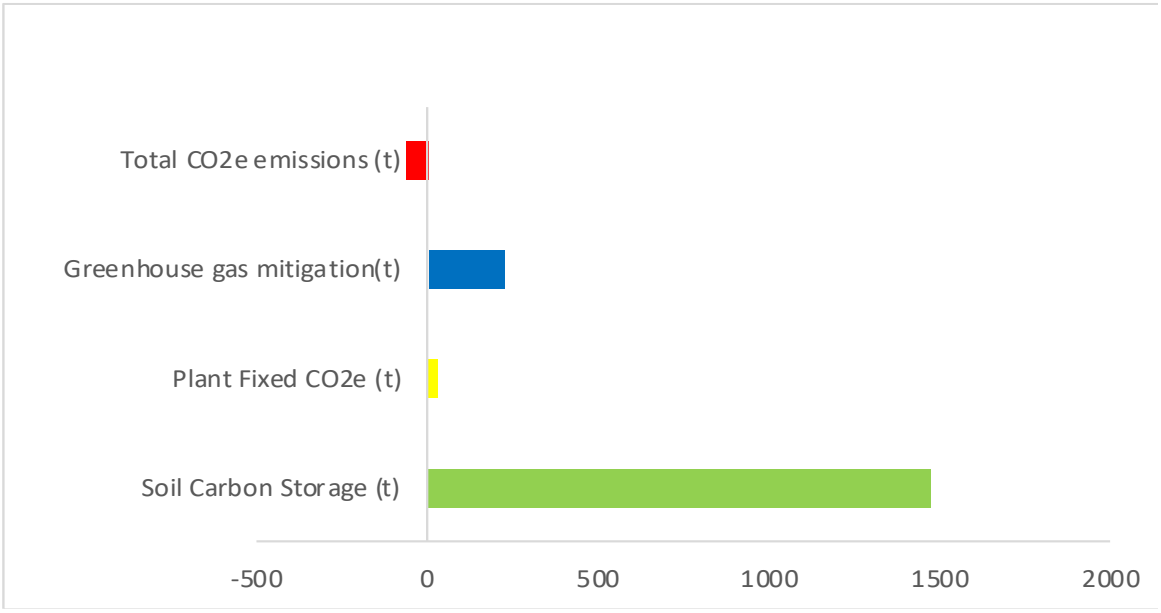

Figure 4.8: Carbon sequestration potential and emission reduction for the regional pyrolysis system at 500°C operating temperature

4.4 Techno-economic analysis (TEA)

The techno-economic analysis follows the framework developed by Roberts et al. (2010) to determine the net profit of the biochar production system based on the functional unit of one dry tonne of biomass. In this work, economic analyses were conducted for the same four scenarios covered in Section 4.3: single farm pyrolysis (Scenario 1), regional farm pyrolysis (Scenario 2), single farm co-pyrolysis (Scenario 3) and regional farm co-pyrolysis (Scenario 4). Each of these scenarios has three different variations based on assumed low, median and high values of the biochar produced, which includes both the value of the material as a commercially sold product and its value as a carbon sequestration medium that commands some "price" through the carbon credit market. It is beyond the scope of this research to attempt to accurately quantify the present or future biochar value but conducting the analysis over a wide range will reveal the extent to which biochar value impacts overall economic viability.

The analysis starts with the full economic model equation described by Roberts et al. (2010):

$$\boldsymbol{\pi = BC + E + Tip + Av - F - Trans - O - C - A - LS} \qquad \text{(Eq. 1)}$$

where $\boldsymbol{\pi}$ is the profit from 1 dry tonne of biomass feedstock, ***BC*** is the value derived from the biochar, ***E*** is the value of the energy created in the process, ***Tip*** is value obtained from any tipping or disposal fees received for the feedstock, ***Av*** is the avoided cost of composting (for yard waste only), ***F*** is the cost of producing or collecting the feedstock, ***Trans*** is the transportation cost for both the feedstock and the biochar product, ***C*** is the capital cost associated with processing a unit of the feedstock, ***O*** is the operating cost incurred for processing a unit of the feedstock, ***A*** is the

cost of applying the biochar to the field, and ***LS*** is the lost sales (for yard waste compost only). This model is applicable to much larger systems than the Biogenic Refinery used as the basis for this study (Figure 4.1). Therefore, some assumptions had to be made to frame a representative equation for this particular system for the different scenarios

Model Assumptions

1. ***E*** is omitted because the modeled thermochemical conversion system generates biochar only and no energy co-products.
2. ***Tip*** is omitted because with the single farm scenario, only waste at a single farm is used to produce biochar. In the regional Scenario, it was assumed that farms generating waste transport it at their cost to the central farm operating the pyrolysis facility. Therefore, no tip fees are paid by farms generating waste.
3. ***Av*** is omitted because only waste feedstocks are used and thus the cost of production is zero. The cost of collecting feedstock on a single farm is assumed negligible and the farm producing biochar does not pay the cost of collection for waste generated at other regional farms.
4. ***F*** is omitted because only waste feedstocks are used and thus the cost of production is zero. The cost of collecting feedstock on a single farm is assumed negligible, and the central farm producing biochar does not pay the cost of collection for waste generated at other regional farms.
5. ***Trans*** is omitted because the cost of transporting feedstock and biochar on a single farm is assumed negligible, and the central farm producing biochar does not pay the cost of transportation for waste generated at other regional farms.

6. ***A*** is omitted because the cost of biochar application on a single farm is assumed negligible, and excess biochar which is more than can be applied at the central farm operating the pyrolysis facility is offered for sale on-site.
7. ***LS*** is omitted because none of the waste streams considered in this analysis are typically sent to composting facilities.

Based on the assumptions outlined above, our simplified biochar net profit relation is:

$$\boldsymbol{\pi = BC + DA - C - O} \qquad \text{(Eq. 2)}$$

where ***DA*** represents the disposal avoidance for landfilling LDPE mulch film and is added to the Roberts model as an effective revenue stream. As mentioned above, ***BC*** is the value derived from biochar, comprised of two contributions: sale of excess biochar at low/median/high price, and value of GHG reductions through carbon credits. It was assumed that an appropriate range for the price of biochar in this model was $50 to $500, with $50 per tonne being the lowest value at which the farmer could sell the excess of biochar produced, $200 per tonne being a reasonable median value based on current markets (Dickinson et al., 2015), and $500 as the highest value that can be obtained per tonne of biochar produced, considering the future expected availability of carbon credits applied to biochar production. Farm A (Figure 4.2) was again used as the location of the centralized pyrolysis facility. The fertilizer value of material added on-site to crops that use plastic mulch over 8 acres at Farm A was considered to be included in the low/median/high biochar values specified above. The data used in this model was based specifically on the 500°C conversion

temperature that provided the highest yield and overall carbon sequestration potential (Tables 4.4 and 4.5).

Table 4.6 provides all of the data inputs, assumptions and sources used for computation of net biochar profit per dry tonne of biomass, as represented by Equation 2. The general approach was based on the assumption that the farm operating the centralized pyrolysis facility (Farm A) uses on-site produced biochar to first apply to soil used for growing crops requiring mulch film, and then sells any excess material. In the case of co-pyrolysis operation, the conservative assumption made was that the biochar thus generated is not be suitable for soil amendment and therefore cannot be sold for profit. This material would be applied to non-agricultural land on the farm, with an assumed negligible cost of application. When considering the regional scenarios with an order of magnitude greater biomass processed than on the single Farm A, the same amount of biochar is used on-site for soil amendment, but now a much larger amount is available for sale. Based on the analysis outlined in Table 4.6, the biochar available for sale in single farm pyrolysis, single farm co-pyrolysis, regional pyrolysis and regional co-pyrolysis scenarios is 42.9, 41.8, 710.7 and 700.3 t/year, respectively.

The capital and operating costs of the pyrolysis equipment (***C*** and ***O*** in Equation 2) are expectedly major contributors to the net biochar profit computations, but these parameters are often difficult to quantify because companies tend not to disclose this information in open academic or technical literature. For the single farm scenarios, the Biomass Controls equipment owned by RIT (Figure 4.2) was used as a benchmark and the capital cost is known because of the company's specified donation value from 2018. To determine equipment capital cost for the regional scenarios where

10 times greater biomass is processed, the study relied on the relation developed by Bridgwater et al. (2002) for total pyrolysis plant cost (*TPC*), also used in the analysis of Roberts et al. (2010):

$$TPC\,(2000\ \text{kEuros}) = 40.8 \times (Q_{f,dry} \times 1000)^{0.6194} \qquad \text{(Eq. 3)}$$

where $Q_{f,dry}$ is the mass flow rate of biomass feedstock in dry tonne per hour. After applying Equation 3, the result was converted from Euros to U.S. dollars in year 2000 (0.9231 €/$; Roberts et al., 2010) and then multiplied by 1.5012 to account for inflation from 2000 to 2020 (from https://smartasset.com/investing/inflation-calculator, based on 2.06% average inflation rate and cumulative inflation of 50.12%). In addition to the pyrolysis system itself, it is also necessary to include the cost of pretreatment equipment required for feedstock drying, grinding, etc. Roberts et al. (2010) recommended a pretreatment equipment capital cost of \$4.12 \$ t^{-1} DM, but they were modeling much larger systems, capable of handling much more feedstock per day. To be conservative in the current analysis, a 10X larger cost per dry tonne was assumed for both the single farm and regional scenarios, then multiplied by a factor of 1.2467 to account for 2007 to 2020 inflation. The total capital cost (based on the combination of pretreatment and pyrolysis equipment) was finally converted to annual capital cost using the relation

$$C_{annual} = C_{total}/[1/r - 1/r(1+r)^n] \qquad \text{(Eq. 4)}$$

where a 5% discount rate (r) was assumed (consistent with Roberts et al., 2010) and the system lifetime (n) was assumed to be 20 years. Estimating operation cost ($\boldsymbol{O}$) is often much more complex because it is dictated by the specific equipment scale, associated subsystems and operating

protocol. Therefore, the value \$31.58 \$ t^{-1} DM was used, as recommended as the highest and most conservative value by Roberts et al. (2010).

Because our entire research effort was motivated by developing a process to handle agricultural mulch film (AMF) at the end of the growing season, it was necessary for the economic model to comprehend the effective "revenue" produced by avoiding cost of AFM landfilling. Here again, the data provided by Farm A was used, indicating 1.2 t of mulch film applied per year with assumed landfill tip fee of \$85/t. This landfill fee was combined with a weekly rate for dumpster rental provided by local waste hauling companies, to arrive at the annual displaced cost of \$500 for AFM disposal.

Table 4.6 – Techno-economic analysis model input parameters, assumptions and computations for single farm and regional pyrolysis systems. This analysis generally follows the framework of Roberts et al. (2010) for computing net profit of biochar production in Upstate New York

Parameter	Value	Units	Comments
Land area for biochar application at single farm (Farm A)	3.2	hm^2	Assume Farm A uses biochar only on crops that require mulch films (8 acres).
Biochar applied at single farm	32	t	Assuming 10 t hm^{-2} application.
Single farm available biomass	255.6	t	Data from Farm A, including apple tree trimmings, crop residue, wooden pallets and cardboard.
Single farm dry biomass	230.04	t	Assuming 10% moisture content.
Single farm biochar production (pyrolysis)	74.9	t	Based on empirical yield.
Single farm biochar available for sale (pyrolysis)	42.9	t	Extra biochar after application to 8 acres (3.2 hm^2) on-site for crops that use mulch films.

Single farm biochar production (co-pyrolysis)	73.8	t	Based on empirical yield, excluding biochar produced via 75:25 co-pyrolysis.
Single farm biochar available for sale (co-pyrolysis)	41.8	t	Extra biochar after application to 8 acres (3.2 hm^2) on-site for crops that use mulch films.
Regional biomass	2556	t	Assuming 10X single farm value.
Regional dry biomass	2,300	t	10X single farm value, assuming 10% moisture content.
Regional biochar production (pyrolysis)	742.7	t	Based on empirical yield, with 10X available biomass.
Regional biochar available for sale (pyrolysis)	710.7	t	Extra biochar after application to 8 acres on-site.
Regional biochar production (co-pyrolysis)	732.3	t	Based on empirical yield, excluding biochar produce via 75:25 co-pyrolysis.
Regional biochar available for sale (co-pyrolysis)	700.3	t	Extra biochar after application to 8 acres on-site.
Low biochar value	50	$/t	Combines sale price at farm, value of GHG reductions through carbon credits and fertilizer value.
Median biochar value	200	$/t	
High biochar value	500	$/t	
Disposal avoidance (DA)	500	$/year	Based on 1.2 t LDPE x \$85 t^{-1} landfill tip fee, plus dumpster rental for 1 week.
Capital cost of pretreatment equipment (Scenarios 1&3)	11,816	$	Applied 10X factor to figure of \$4.12 \$ t^{-1} DM proposed by Roberts et al. (2010) for much larger systems, multiplied by factor of 1.2467 to account for inflation 2007 to 2020 (https://smartasset.com/investing/inflation-calculator).
Capital cost of pyrolysis equipment (Scenarios 1&3)	300,000	$	Value of Biogenic Refinery; note significantly less than value from Bridgwater et al. (2002) relation; see Section 4.5.
Total capital cost (Scenarios 1&3)	311,816	$	Pre-treatment + pyrolysis.

Annual capital cost of pre-treatment and pyrolysis equipment (Scenarios 1&3)	25,021	$	Equation (6) in Supporting Information of Roberts et al. (2010).
Combined annual O&M cost of pre-treatment and pyrolysis equipment (Scenarios 1&3)	9,057	$	Used figure of \$31.58 \$ t^{-1} DM proposed by Roberts et al. (2010), multiplied by factor of 1.2467 to account for 2007 to 2020 inflation (https://smartasset.com/investing/inflation-calculator).
Capital cost of pretreatment equipment (Scenarios 2&4)	118,158	$	Applied 10X factor to figure of \$4.12 \$ t^{-1} DM proposed by Roberts et al. (2010) for much larger systems, multiplied by factor of 1.2467 to account for 2007 to 2020 inflation (https://smartasset.com/investing/inflation-calculator).
Capital cost of pyrolysis equipment (Scenarios 2&4)	2,400,988	$	Derived from relation of Bridgwater et al. (2002), p. S19 in Roberts et al. (2010).
Total capital cost (Scenarios 2 &4)	2,519,146	$	Pre-treatment + pyrolysis.
Annual capital cost of pre-treatment and pyrolysis equipment (Scenarios 2 &4)	202,143	$	Equation (6) in Supporting Information of Roberts et al. (2010).
Combined annual O&M cost of pre-treatment and pyrolysis equipment (Scenarios 2 & 4)	90,569	$	Used figure of \$31.58 \$ t^{-1} DM proposed by Roberts et al. (2010), multiplied by factor of 1.2467 to account for 2007 to 2020 inflation (https://smartasset.com/investing/inflation-calculator).
Lifetime of equipment	20	years	Roberts et al. (2010).
Discount rate	5	%	Roberts et al. (2010).

From the data inputs, assumptions and computations summarized in Table 4.6, the overall net biochar profit values per dry tonne of biomass are presented in Figure 4.9. As expected, the assumed biochar value and system scale have dominant influences on the overall economic viability of the modeled farm-based pyrolysis system. In the case of biomass pyrolysis (i.e., no LPDE mulch film), the only profitable case is for regional feedstock processing (assuming 2556 t/year; Table 4.3) with assumed high biochar value of $500/t. The net profit in this case is $27 per tonne of dry biomass. When mulch film co-pyrolysis is included at a 75:25 biomass-to-LDPE ratio, approximately 4 days of biochar production are lost per year and thus the net biochar profit values decrease slightly, with the only profitable case again being for the high biochar value case that produces a net profit of $25 per tonne of dry biomass. At first glance, this seemingly insignificant result does not make a strong case for deploying a farm-scale co-pyrolysis system. However, in the context of a smallholder farm operating the system to process around 2500 tons of regional biomass per year, the total annual profit exceeding $57,000 is compelling, and certainly worthy of consideration as a secondary revenue stream that could enhance the viability of the overall agricultural operation. With the carbon credit markets still at its infancy and growing interest in biochar as a soil amendment, there may be value in deploying pyrolysis capacity that could help farmers reach larger markets.

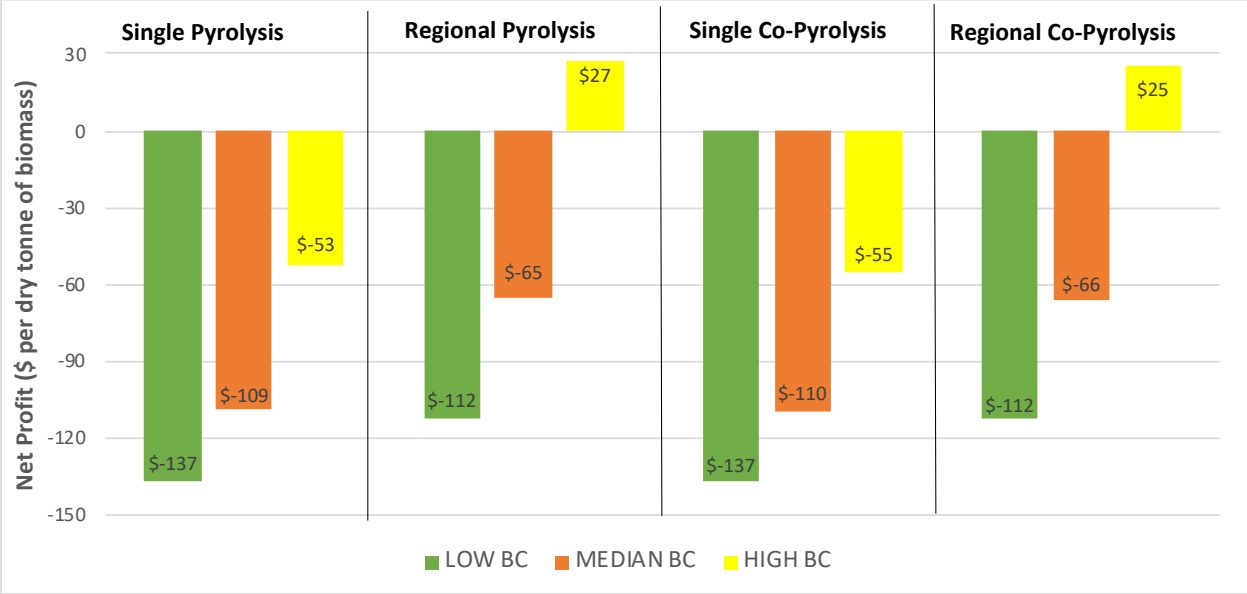

Figure 4.9 –Net profit ($ t^{-1} dry biomass) for the four scenarios, following method of Roberts et al. (2010), with Low/Median/High value of biochar = $50, $200 and $500 $ t^{-1}.

4.5 Assessment of model results

The carbon sequestration and techno-economic analyses presented in Sections 4.3 and 4.4 have demonstrated that under certain conditions a farm-based co-pyrolysis system can provide meaningful sustainability benefits and should be considered as a potential alternative to conventional disposal practices for agricultural waste resources, including both biomass and LDPE mulch films. Here additional assessment is included to put the results in the context of prior studies and practical considerations of deploying co-pyrolysis at scale:

- The models presented in Sections 4.3 and 4.4 do not comprehend important logistical effects, such as when wastes are actually generated throughout the year. Although it was implicitly assumed that a consistent amount of feedstock is available for processing each day, in actuality it is highly variable and seasonal, with the most wastes likely available at the end of the growing season.

- Although the presented models accounted for the effect of system size on capital and operating costs, there is significant uncertainty because such data are generally not readily available for commercial systems. Equipment manufacturers typically favor larger system that offer economies of scale, so much less development has occurred for relatively small systems that may be suitable for operation at the scale of a single farm or cooperative group of farms in close proximity. As illustrated in Figure 4.10, the relation for total pyrolysis capital cost (*TPC*) developed by Bridgwater et al. (2002) shows a very strong influence of system feedstock capacity (t/day) on the effective annual pyrolysis system capital cost per tonne of feedstock processed. Although increasing capacity by a factor of ten from the single farm to regional scenarios greatly reduces normalized equipment cost, further cost reduction (and thus greater net biochar profit) could be realized by increasing processing capacity to 40 t/day or more.
- It is assumed that the biochar generated from the four target agricultural waste biomass streams (crop residues, woody biomass, pallet wood and cardboard) is suitable for soil amendment. However, more research is needed to determine the actual biochar value that would depend on the level of key nutrients (organic carbon, nitrogen, phosphorous, potassium) present in material produced at scale, and how these values compare to other commercial fertilizer options. Also, there is significant uncertainty in the trajectory of carbon removal credits that may be applied to biochar production, but the current trend toward deep decarbonization in California, New York and many European and Asian countries suggests that the carbon sequestration potential of biochar will offer greater value in the future.

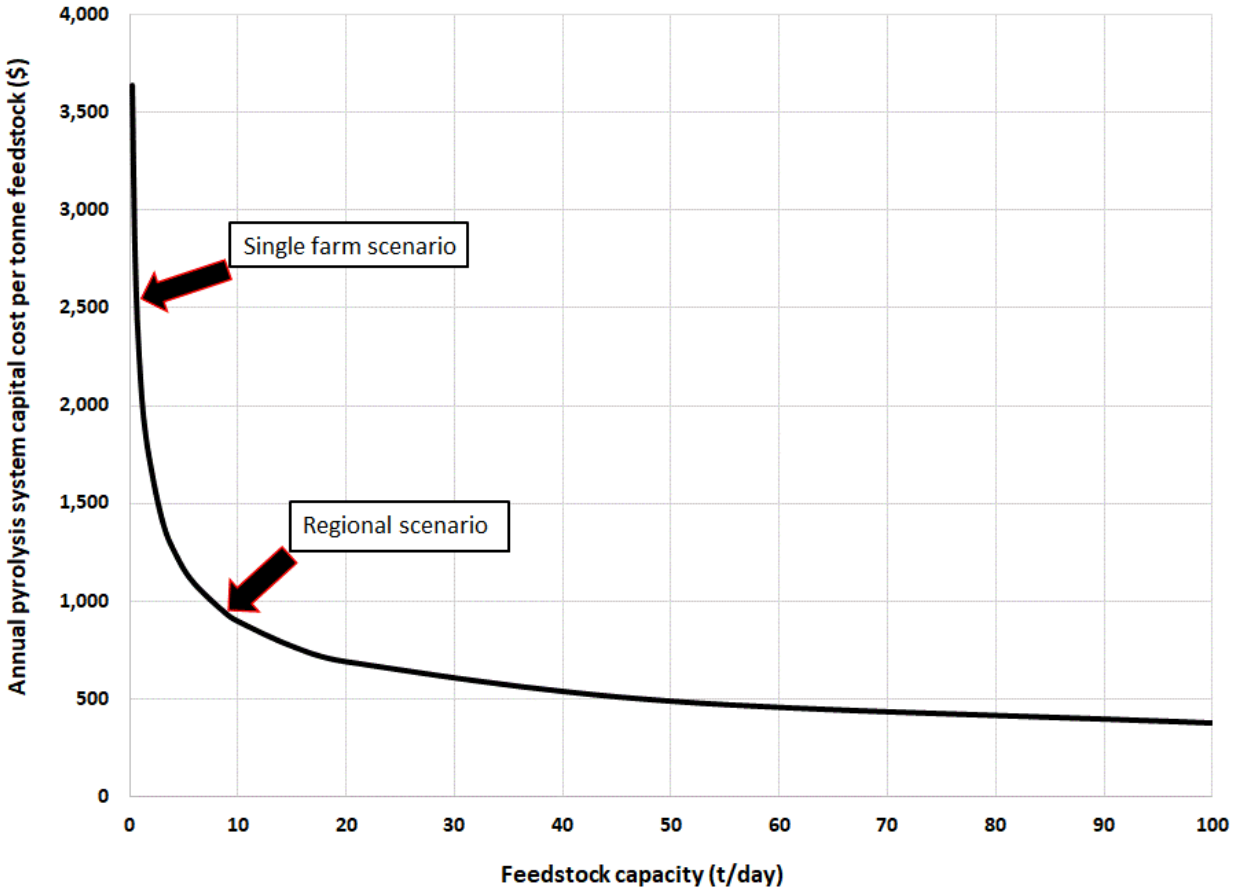

Figure 4.10 – Annual pyrolysis system cost per ton of feedstock, as a function of feedstock capacity (2020 US dollars). Derived from the relation of Bridgwater et al. (2002), with assumed discount rate of 5% and 20-year equipment lifetime.

CHAPTER 5

CONCLUSIONS & FUTURE WORK

To enhance the long-term sustainability of the national and global agricultural system, it is necessary to efficiently utilize water, energy and material resources, while being mindful of minimizing waste. Large volumes of biomass wastes are generated on farms, all of which can be valorized to produce additional revenue to the farmer if properly managed and converted into value-added products. One of the technologies available to convert biomass wastes is pyrolysis, whereby material is processed at high temperature in the absence of oxygen to create multiple co-products including biochar, hydrogen-rich syngas, and liquid bio-oils. Biochar is a highly stable carbonaceous material that can be used in many agricultural, environmental and industrial applications.

This research has considered waste management challenges on typical farms in Upstate New York that generates crop residues, woody biomass from tree trimmings, wooden pallets and cardboard boxes. Additionally, included in the portfolio of farm-generated waste was agricultural mulch film (AMF) film used on many row crops to manage weeds and insects while controlling soil temperature and water content. A laboratory furnace was operated from 500 to 800^{o}C with a pure nitrogen environment to produce a wide variety of biochar materials from the four different biomass wastes materials, and in some cases blending with either 5 or 25 wt.% AFM material manufactured from low density polyethylene (LDPE). It has been demonstrated that most of the organic biomass waste materials produce biochar with relatively high organic carbon content (>80%), low hydrogen-to-carbon ratio (H:C), and very low concentrations of heavy metals and

other contaminants. The results indicate that these waste material feedstocks can be used to produce biochar suitable for soil amendment and other agricultural applications. Hemp meal, selected as a representative crop residue, produced biochar with a much lower organic carbon content, but very high levels of critical nitrogen, phosphorous and potassium nutrients. The high N/P/K nutrient content suggests that a possible development pathway may be to combine biochar from hemp meal and woody biomass (with <90% organic carbon) to produce a sustainable blend that can potentially compete with existing commercial biochar products such as Aries Green®. Even when co-pyrolyzing hemp meal and woody biomass with LDPE mulch films at up to 25 wt%, the biochar properties were largely unchanged and apparently still suitable for soil applications, despite the published guidance from biochar governing bodies that non-biomass feedstock should not be used.

A significant aspect of this thesis research has been to evaluate the overall sustainability of a hypothetical farm-based co-pyrolysis system. Once the technical viability was established based on laboratory-scale experiments, the empirical results were used in concert with data and assumptions from publications by Roberts et al. (2010) and Feng et al. (2020) to conduct carbon sequestration and techno-economic analyses. The carbon sequestration analysis showed that net reduction in CO_{2e} emissions is achievable at all pyrolysis processing temperatures in either single farm or regional scenarios. For single farm pyrolysis, the overall greenhouse gas (GHG) mitigation potential ranges from about 160 to 190 t CO_{2e}/year, with the higher value corresponding to lower pyrolysis temperature (500^{o}C) where yield is highest. However, the impact factor (t CO_{2e}/t biochar) is highest at 800^{o}C because of the higher biochar organic carbon content. As expected, substantially greater GHG mitigation potential is achievable with the regional scenario (~1500 to

1700 t CO_{2e}/year), but the impact factors are slightly lower because of the emissions associated with collecting and transporting waste biomass for neighboring farms. It is pertinent to note that the computed impact factors align well with the lower end of the range reported by Roberts et al. (2010), who modeled much larger pyrolysis systems that valorize both biochar and energy co-products, the latter displacing fossil fuel usage.

Following a similar modeling framework, the general techno-economic model of Roberts et al. (2010) was used to determine the net biochar profit per tonne of dry biomass feedstock, based on 500^{o}C processing temperature where overall carbon sequestration potential was greatest. The results showed that economic viability is achievable only when processing a greater amount of waste feedstock in the regional scenario (nominally 2500 t/year), and assuming a relatively high biochar value of $500/t that includes both commercial sale price and carbon credit value.

To continue to improve understanding of biochar generated from co-pyrolysis processes and inform future development of thermochemical technology at small- to medium-scale, ongoing work would be recommended in the following areas:

- To further understand and quantify the properties of the biochar generated by co-pyrolysis, it is recommended that future toxicant analysis be conducted to test for the presence of potential contaminants such as dioxins, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbon (PAHs).
- Based on the measured biochar properties for the various feedstocks (especially crop residues and woody biomass that exist in the greatest quantities), determine what nutrient blends are achievable compared to biochar products currently available on the market.

- Evaluate potential uses of biochar in other industries that may command a greater value than its use as a soil amendment. For example, our prior biochar research has demonstrated potential as magnetic material in electrochemical devices (Rodriguez Alberto et al., 2019) and in biochar-bioplastic composites (Diaz et al., 2020).
- Assess in real-time the impact of debris on the agricultural mulch film when it is pulled from the field and the overall impact on the biochar quality produced from co-pyrolysis.
- More fully analyze the effect of scale and determine if new opportunities exist for improving economic viability at smaller scale where biochar sales could directly benefit smallholder farmers. Part of this analysis will be informed by rapidly evolving policy changes regarding carbon credits at the State and Federal levels.

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APPENDIX A

International Biochar Initiative (IBI) Tests for Certification Program – Commercial Material

APPENDIX A.1: **Pallet wood biochar produced at commercial scale**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No: 9554
Batch: DEC 2016 C
CODE: BioChar IBI

Lincoln Young
Rockwood Recycling
P.O. Box 998
Lebanon

Date Received: 12/14/2016
Sample ID: Sample 1
Lab ID. Number: 6120462-01

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

	Dry Basis Unless Stated:	Range	Units	Method
Moisture (time of analysis)	2.7		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	8.0		lb/cu ft	
Organic Carbon	88.7		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.39	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	2.7		% of total dry mass	ASTM D-1762-84
Total Nitrogen	1.09		% of total dry mass	Dry Combustion
pH value	9.86		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	0.426		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	5.5		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	2.0		%CaCO3	ASTM D 4373
Butane Act.	4.9		g/100g dry	ASTM D 5742-95
Surface Area Correlation	288		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	1.8	13 to 100	0.70	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.28	J
Chromium	(Cr)	4.0	93 to 1200	0.70	J
Cobalt	(Co)	**ND**	34 to 100	0.70	J
Copper	(Cu)	103	143 to 6000	0.70	J
Lead	(Pb)	2.8	121 to 300	0.28	J
Molybdenum	(Mo)	1.2	5 to 75	0.70	J
Mercury	(Hg)	**ND**	1 to 17	0.0015	EPA 7471
Nickel	(Ni)	2.0	47 to 420	0.70	J
Selenium	(Se)	**ND**	2 to 200	1.40	J
Zinc	(Zn)	99.6	416 to 7400	1.40	J
Boron	(B)	21.1	Declaration	7.02	TMECC
Chlorine	(Cl)	1027	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	701.6	E
Iron	(Fe)	1302	Declaration	35.1	E
Manganese	(Mn)	174	Declaration	0.70	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	0.4	percent	F
0.5-1mm	0.5	percent	F
1-2mm	7.2	percent	F
2-4mm	36.8	percent	F
4-8mm	41.0	percent	F
8-16mm	14.1	percent	F
16-25mm	0.0	percent	F
25-50mm	0.0	percent	F
>50mm	0.0	percent	F

Basic Soil Enhancement Properties			
Total (K)	3464	mg/kg	E
Total (P)	1918	mg/kg	E
Ammonia (NH4-N)	3.7	mg/kg	A
Nitrate (NO3-N)	1.4	mg/kg	A
Organic (Org-N)	10936	mg/kg	Calc.
Volatile Matter	7.7	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
B Enders & Lehmann
C Wang after Rajan
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B

International Biochar Initiative (IBI) Tests for Certification Program – In-House Materials

APPENDIX B.1: **Raw HM**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No: 11261
Batch: DEC 20 D
CODE: BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Raw Hemp Meal
Lab ID. Number: 0120576-01

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

	Dry Basis Unless Stated:	Range	Units	Method
Moisture (time of analysis)	9.4		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	14.6		lb/cu ft	
Organic Carbon	44.4		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	1.36	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	13.5		% of total dry mass	ASTM D-1762-84
Total Nitrogen	3.99		% of total dry mass	Dry Combustion
pH value	6.99		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	2.45		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	11.1		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	4.0		%CaCO3	ASTM D 4373
Butane Act.	2.4		g/100g dry	ASTM D 5742-95
Surface Area Correlation	208		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.50	J
Cadmium	(Cd)	0.3	1.4 to 39	0.20	J
Chromium	(Cr)	0.8	93 to 1200	0.50	J
Cobalt	(Co)	**ND**	34 to 100	0.50	J
Copper	(Cu)	14.5	143 to 6000	0.50	J
Lead	(Pb)	0.7	121 to 300	0.20	J
Molybdenum	(Mo)	2.0	5 to 75	0.50	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	3.0	47 to 420	0.50	J
Selenium	(Se)	**ND**	2 to 200	1.00	J
Zinc	(Zn)	57.2	416 to 7400	1.00	J
Boron	(B)	55.2	Declaration	5.00	TMECC
Chlorine	(Cl)	1502	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	500.0	E
Iron	(Fe)	219	Declaration	25.0	E
Manganese	(Mn)	167	Declaration	0.50	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	N/A	percent	F
0.5-1mm	N/A	percent	F
1-2mm	N/A	percent	F
2-4mm	N/A	percent	F
4-8mm	N/A	percent	F
8-16mm	N/A	percent	F
16-25mm	N/A	percent	F
25-50mm	N/A	percent	F
>50mm	N/A	percent	F
Basic Soil Enhancement Properties			
Total (K)	17220	mg/kg	E
Total (P)	4716	mg/kg	E
Ammonia (NH4-N)	529	mg/kg	A
Nitrate (NO3-N)	425	mg/kg	A
Organic (Org-N)	38933	mg/kg	Calc.
Volatile Matter	73.8	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.2: **HM500C**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Hemp Meal at 500 C
Lab ID. Number: 0120576-02

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

	Dry Basis Unless Stated:	Range	Units	Method
Moisture (time of analysis)	4.0		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	12.0		lb/cu ft	
Organic Carbon	45.1		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.71	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	34.1		% of total dry mass	ASTM D-1762-84
Total Nitrogen	4.02		% of total dry mass	Dry Combustion
pH value	11.98		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	4.01		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	33.5		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	17.6		%CaCO3	ASTM D 4373
Butane Act.	1.4		g/100g dry	ASTM D 5742-95
Surface Area Correlation	178		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.45	J
Cadmium	(Cd)	0.4	1.4 to 39	0.18	J
Chromium	(Cr)	0.6	93 to 1200	0.45	J
Cobalt	(Co)	**ND**	34 to 100	0.45	J
Copper	(Cu)	27.0	143 to 6000	0.45	J
Lead	(Pb)	1.8	121 to 300	0.18	J
Molybdenum	(Mo)	4.0	5 to 75	0.45	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	7.8	47 to 420	0.45	J
Selenium	(Se)	**ND**	2 to 200	0.90	J
Zinc	(Zn)	159	416 to 7400	0.90	J
Boron	(B)	113	Declaration	4.50	TMECC
Chlorine	(Cl)	2599	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	450.5	E
Iron	(Fe)	573	Declaration	22.5	E
Manganese	(Mn)	541	Declaration	0.45	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	N/A	percent	F
0.5-1mm	N/A	percent	F
1-2mm	N/A	percent	F
2-4mm	N/A	percent	F
4-8mm	N/A	percent	F
8-16mm	N/A	percent	F
16-25mm	N/A	percent	F
25-50mm	N/A	percent	F
>50mm	N/A	percent	F

Basic Soil Enhancement Properties			
Total (K)	51432	mg/kg	E
Total (P)	14468	mg/kg	E
Ammonia (NH4-N)	13.8	mg/kg	A
Nitrate (NO3-N)	2.2	mg/kg	A
Organic (Org-N)	40168	mg/kg	Calc.
Volatile Matter	30.9	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.3: **HM800C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Hemp Meal at 800 C
Lab ID. Number: 0120576-03

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

Dry Basis Unless Stated:		Range	Units	Method
Moisture (time of analysis)	-0.1		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	11.7		lb/cu ft	
Organic Carbon	47.0		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.44	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	44.0		% of total dry mass	ASTM D-1762-84
Total Nitrogen	3.52		% of total dry mass	Dry Combustion
pH value	12.60		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	9.50		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	35.3		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	5.8		%CaCO3	ASTM D 4373
Butane Act.	0.9		g/100g dry	ASTM D 5742-95
Surface Area Correlation	161		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.43	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.17	J
Chromium	(Cr)	0.6	93 to 1200	0.43	J
Cobalt	(Co)	**ND**	34 to 100	0.43	J
Copper	(Cu)	12.5	143 to 6000	0.43	J
Lead	(Pb)	0.2	121 to 300	0.17	J
Molybdenum	(Mo)	2.5	5 to 75	0.43	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	2.7	47 to 420	0.43	J
Selenium	(Se)	**ND**	2 to 200	0.85	J
Zinc	(Zn)	54.7	416 to 7400	0.85	J
Boron	(B)	127.1	Declaration	4.27	TMECC
Chlorine	(Cl)	705	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	427.4	E
Iron	(Fe)	460	Declaration	21.4	E
Manganese	(Mn)	526	Declaration	0.43	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	N/A	percent	F
0.5-1mm	N/A	percent	F
1-2mm	N/A	percent	F
2-4mm	N/A	percent	F
4-8mm	N/A	percent	F
8-16mm	N/A	percent	F
16-25mm	N/A	percent	F
25-50mm	N/A	percent	F
>50mm	N/A	percent	F
Basic Soil Enhancement Properties			
Total (K)	62248	mg/kg	E
Total (P)	12043	mg/kg	E
Ammonia (NH4-N)	9.8	mg/kg	A
Nitrate (NO3-N)	14.3	mg/kg	A
Organic (Org-N)	35162	mg/kg	Calc.
Volatile Matter	16.1	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.4: **HMFM (95/5) 500C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Hemp Meal + LDPE Film (95/5) at 500 C
Lab ID. Number: 0120576-06

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

Dry Basis Unless Stated:		Range	Units	Method
Moisture (time of analysis)	4.7		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	11.9		lb/cu ft	
Organic Carbon	48.8		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.64	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	37.5		% of total dry mass	ASTM D-1762-84
Total Nitrogen	4.21		% of total dry mass	Dry Combustion
pH value	10.46		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	2.71		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	35.8		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	16.2		%CaCO3	ASTM D 4373
Butane Act.	0.5		g/100g dry	ASTM D 5742-95
Surface Area Correlation	148		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.41	J
Cadmium	(Cd)	0.5	1.4 to 39	0.16	J
Chromium	(Cr)	0.5	93 to 1200	0.41	J
Cobalt	(Co)	**ND**	34 to 100	0.41	J
Copper	(Cu)	26.1	143 to 6000	0.41	J
Lead	(Pb)	1.9	121 to 300	0.16	J
Molybdenum	(Mo)	4.1	5 to 75	0.41	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	8.7	47 to 420	0.41	J
Selenium	(Se)	**ND**	2 to 200	0.82	J
Zinc	(Zn)	189	416 to 7400	0.82	J
Boron	(B)	124	Declaration	4.10	TMECC
Chlorine	(Cl)	1852	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	409.8	E
Iron	(Fe)	631	Declaration	20.5	E
Manganese	(Mn)	549	Declaration	0.41	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	N/A	percent	F
0.5-1mm	N/A	percent	F
1-2mm	N/A	percent	F
2-4mm	N/A	percent	F
4-8mm	N/A	percent	F
8-16mm	N/A	percent	F
16-25mm	N/A	percent	F
25-50mm	N/A	percent	F
>50mm	N/A	percent	F

Basic Soil Enhancement Properties			
Total (K)	58721	mg/kg	E
Total (P)	16041	mg/kg	E
Ammonia (NH4-N)	2.9	mg/kg	A
Nitrate (NO3-N)	2.5	mg/kg	A
Organic (Org-N)	42128	mg/kg	Calc.
Volatile Matter	27.6	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.5: **HMFM (75/25) 500C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No: 11261
Batch: DEC 20 D
CODE: BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Hemp Meal + LDPE Film (75/25) at 500 C
Lab ID. Number: 0120576-04

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

	Dry Basis Unless Stated:	Range	Units	Method
Moisture (time of analysis)	5.8		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	12.7		lb/cu ft	
Organic Carbon	46.1		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.74	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	33.4		% of total dry mass	ASTM D-1762-84
Total Nitrogen	3.75		% of total dry mass	Dry Combustion
pH value	11.98		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	4.11		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	31.7		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	17.4		%CaCO3	ASTM D 4373
Butane Act.	1.3		g/100g dry	ASTM D 5742-95
Surface Area Correlation	175		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.49	J
Cadmium	(Cd)	0.2	1.4 to 39	0.20	J
Chromium	(Cr)	0.7	93 to 1200	0.49	J
Cobalt	(Co)	**ND**	34 to 100	0.49	J
Copper	(Cu)	24.4	143 to 6000	0.49	J
Lead	(Pb)	1.7	121 to 300	0.20	J
Molybdenum	(Mo)	3.8	5 to 75	0.49	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	7.1	47 to 420	0.49	J
Selenium	(Se)	**ND**	2 to 200	0.98	J
Zinc	(Zn)	250	416 to 7400	0.98	J
Boron	(B)	111	Declaration	4.90	TMECC
Chlorine	(Cl)	2838	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	490.2	E
Iron	(Fe)	530	Declaration	24.5	E
Manganese	(Mn)	466	Declaration	0.49	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	N/A	percent	F
0.5-1mm	N/A	percent	F
1-2mm	N/A	percent	F
2-4mm	N/A	percent	F
4-8mm	N/A	percent	F
8-16mm	N/A	percent	F
16-25mm	N/A	percent	F
25-50mm	N/A	percent	F
>50mm	N/A	percent	F

Basic Soil Enhancement Properties			
Total (K)	45402	mg/kg	E
Total (P)	11931	mg/kg	E
Ammonia (NH4-N)	23.7	mg/kg	A
Nitrate (NO3-N)	2.2	mg/kg	A
Organic (Org-N)	37465	mg/kg	Calc.
Volatile Matter	30.9	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.6: **HMFM (95/5) 800C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Hemp Meal + LDPE Film (95/5) at 800 C
Lab ID. Number: 0120576-07

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

Dry Basis Unless Stated:		Range	Units	Method
Moisture (time of analysis)	10.7		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	12.9		lb/cu ft	
Organic Carbon	43.6		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.56	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	40.5		% of total dry mass	ASTM D-1762-84
Total Nitrogen	3.38		% of total dry mass	Dry Combustion
pH value	12.37		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	6.44		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	33.0		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	9.3		%CaCO3	ASTM D 4373
Butane Act.	1.0		g/100g dry	ASTM D 5742-95
Surface Area Correlation	164		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.41	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.16	J
Chromium	(Cr)	0.7	93 to 1200	0.41	J
Cobalt	(Co)	**ND**	34 to 100	0.41	J
Copper	(Cu)	14.4	143 to 6000	0.41	J
Lead	(Pb)	**ND**	121 to 300	0.16	J
Molybdenum	(Mo)	3.2	5 to 75	0.41	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	3.3	47 to 420	0.41	J
Selenium	(Se)	**ND**	2 to 200	0.81	J
Zinc	(Zn)	48.8	416 to 7400	0.81	J
Boron	(B)	130	Declaration	4.07	TMECC
Chlorine	(Cl)	1628	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	406.5	E
Iron	(Fe)	535	Declaration	20.3	E
Manganese	(Mn)	495	Declaration	0.41	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	N/A	percent	F
0.5-1mm	N/A	percent	F
1-2mm	N/A	percent	F
2-4mm	N/A	percent	F
4-8mm	N/A	percent	F
8-16mm	N/A	percent	F
16-25mm	N/A	percent	F
25-50mm	N/A	percent	F
>50mm	N/A	percent	F

Basic Soil Enhancement Properties			
Total (K)	61407	mg/kg	E
Total (P)	11154	mg/kg	E
Ammonia (NH4-N)	9.7	mg/kg	A
Nitrate (NO3-N)	36	mg/kg	A
Organic (Org-N)	33799	mg/kg	Calc.
Volatile Matter	21.1	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.7: **HMFM (75/25) 800C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Hemp Meal + LDPE Film (75/25) at 800 C
Lab ID. Number: 0120576-05

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

Dry Basis Unless Stated:		Range	Units	Method
Moisture (time of analysis)	0.3		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	12.4		lb/cu ft	
Organic Carbon	50.0		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.40	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	41.9		% of total dry mass	ASTM D-1762-84
Total Nitrogen	3.58		% of total dry mass	Dry Combustion
pH value	12.46		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	7.61		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	33.4		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	4.9		%CaCO3	ASTM D 4373
Butane Act.	1.3		g/100g dry	ASTM D 5742-95
Surface Area Correlation	173		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.43	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.17	J
Chromium	(Cr)	0.6	93 to 1200	0.43	J
Cobalt	(Co)	**ND**	34 to 100	0.43	J
Copper	(Cu)	12.5	143 to 6000	0.43	J
Lead	(Pb)	**ND**	121 to 300	0.17	J
Molybdenum	(Mo)	2.1	5 to 75	0.43	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	2.8	47 to 420	0.43	J
Selenium	(Se)	**ND**	2 to 200	0.86	J
Zinc	(Zn)	50.3	416 to 7400	0.86	J
Boron	(B)	98.0	Declaration	4.31	TMECC
Chlorine	(Cl)	818	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	431.0	E
Iron	(Fe)	450	Declaration	21.6	E
Manganese	(Mn)	406	Declaration	0.43	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	N/A	percent	F
0.5-1mm	N/A	percent	F
1-2mm	N/A	percent	F
2-4mm	N/A	percent	F
4-8mm	N/A	percent	F
8-16mm	N/A	percent	F
16-25mm	N/A	percent	F
25-50mm	N/A	percent	F
>50mm	N/A	percent	F

Basic Soil Enhancement Properties			
Total (K)	53759	mg/kg	E
Total (P)	10569	mg/kg	E
Ammonia (NH4-N)	11.5	mg/kg	A
Nitrate (NO3-N)	100	mg/kg	A
Organic (Org-N)	35654	mg/kg	Calc.
Volatile Matter	16.2	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.8: **Raw WP.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No: 11261
Batch: DEC 20 D
CODE: BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Raw Wood Pellets
Lab ID. Number: 0120576-08

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

	Dry Basis Unless Stated:	Range	Units	Method
Moisture (time of analysis)	15.9		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	21.6		lb/cu ft	
Organic Carbon	48.9		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	1.43	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	0.6		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.18		% of total dry mass	Dry Combustion
pH value	12.37		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	0.113		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	4.4		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	0.1		%CaCO3	ASTM D 4373
Butane Act.	0.7		g/100g dry	ASTM D 5742-95
Surface Area Correlation	154		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.48	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.19	J
Chromium	(Cr)	0.7	93 to 1200	0.48	J
Cobalt	(Co)	**ND**	34 to 100	0.48	J
Copper	(Cu)	1.3	143 to 6000	0.48	J
Lead	(Pb)	0.4	121 to 300	0.19	J
Molybdenum	(Mo)	**ND**	5 to 75	0.48	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	0.6	47 to 420	0.48	J
Selenium	(Se)	**ND**	2 to 200	0.96	J
Zinc	(Zn)	4.5	416 to 7400	0.96	J
Boron	(B)	**ND**	Declaration	4.81	TMECC
Chlorine	(Cl)	31.6	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	480.8	E
Iron	(Fe)	**ND**	Declaration	24.0	E
Manganese	(Mn)	27	Declaration	0.48	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	N/A	percent	F
0.5-1mm	N/A	percent	F
1-2mm	N/A	percent	F
2-4mm	N/A	percent	F
4-8mm	N/A	percent	F
8-16mm	N/A	percent	F
16-25mm	N/A	percent	F
25-50mm	N/A	percent	F
>50mm	N/A	percent	F

Basic Soil Enhancement Properties			
Total (K)	1361	mg/kg	E
Total (P)	99	mg/kg	E
Ammonia (NH4-N)	1.4	mg/kg	A
Nitrate (NO3-N)	0.6	mg/kg	A
Organic (Org-N)	1784	mg/kg	Calc.
Volatile Matter	80.2	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.9: **WP500C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Wood Pellets at 500 C
Lab ID. Number: 0120576-09

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

Dry Basis Unless Stated:		Range	Units	Method
Moisture (time of analysis)	3.0		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	14.6		lb/cu ft	
Organic Carbon	83.1		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.56	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	1.4		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.40		% of total dry mass	Dry Combustion
pH value	4.40		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	0.111		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	5.0		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	0.7		%CaCO3	ASTM D 4373
Butane Act.	2.3		g/100g dry	ASTM D 5742-95
Surface Area Correlation	207		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.49	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.20	J
Chromium	(Cr)	**ND**	93 to 1200	0.49	J
Cobalt	(Co)	**ND**	34 to 100	0.49	J
Copper	(Cu)	2.8	143 to 6000	0.49	J
Lead	(Pb)	0.7	121 to 300	0.20	J
Molybdenum	(Mo)	**ND**	5 to 75	0.49	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	14.4	47 to 420	0.49	J
Selenium	(Se)	**ND**	2 to 200	0.98	J
Zinc	(Zn)	7.4	416 to 7400	0.98	J
Boron	(B)	8.5	Declaration	4.90	TMECC
Chlorine	(Cl)	**ND**	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	490.2	E
Iron	(Fe)	83	Declaration	24.5	E
Manganese	(Mn)	45	Declaration	0.49	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	N/A	percent	F
0.5-1mm	N/A	percent	F
1-2mm	N/A	percent	F
2-4mm	N/A	percent	F
4-8mm	N/A	percent	F
8-16mm	N/A	percent	F
16-25mm	N/A	percent	F
25-50mm	N/A	percent	F
>50mm	N/A	percent	F

Basic Soil Enhancement Properties			
Total (K)	2518	mg/kg	E
Total (P)	69	mg/kg	E
Ammonia (NH4-N)	2.6	mg/kg	A
Nitrate (NO3-N)	0.6	mg/kg	A
Organic (Org-N)	4040	mg/kg	Calc.
Volatile Matter	20.7	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.10: **WP650C**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No: 11261
Batch: MAR 21 A
CODE: BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 3/1/2021
Sample ID: Wood Pellets at 650C (WP650C)
Lab ID. Number: 1030013-01

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

Dry Basis Unless Stated:		Range	Units	Method
Moisture (time of analysis)	2.7		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	18.5		lb/cu ft	
Organic Carbon	91.2		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.45	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	1.5		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.54		% of total dry mass	Dry Combustion
pH value	7.72		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	0.161		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	6.5		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	0.8		%CaCO3	ASTM D 4373
Butane Act.	2.0		g/100g dry	ASTM D 5742-95
Surface Area Correlation	196		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.43	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.17	J
Chromium	(Cr)	**ND**	93 to 1200	0.43	J
Cobalt	(Co)	**ND**	34 to 100	0.43	J
Copper	(Cu)	**ND**	143 to 6000	0.43	J
Lead	(Pb)	**ND**	121 to 300	0.17	J
Molybdenum	(Mo)	**ND**	5 to 75	0.43	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	**ND**	47 to 420	0.43	J
Selenium	(Se)	**ND**	2 to 200	0.86	J
Zinc	(Zn)	3.2	416 to 7400	0.86	J
Boron	(B)	**ND**	Declaration	4.29	TMECC
Chlorine	(Cl)	27.5	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	429.0	E
Iron	(Fe)	43	Declaration	21.5	E
Manganese	(Mn)	5	Declaration	0.43	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	11.1	percent	F
0.5-1mm	12.6	percent	F
1-2mm	8.7	percent	F
2-4mm	13.1	percent	F
4-8mm	54.5	percent	F
8-16mm	0.0	percent	F
16-25mm	0.0	percent	F
25-50mm	0.0	percent	F
>50mm	0.0	percent	F

Basic Soil Enhancement Properties			
Total (K)	549	mg/kg	E
Total (P)	4	mg/kg	E
Ammonia (NH4-N)	5.0	mg/kg	A
Nitrate (NO3-N)	1.2	mg/kg	A
Organic (Org-N)	5435	mg/kg	Calc.
Volatile Matter	17.4	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.11: **WP800C**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Wood Pellets at 800 C
Lab ID. Number: 0120576-10

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

Dry Basis Unless Stated:		Range	Units	Method
Moisture (time of analysis)	3.3		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	15.6		lb/cu ft	
Organic Carbon	93.2		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.23	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	1.6		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.76		% of total dry mass	Dry Combustion
pH value	5.93		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	0.491		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	6.2		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	2.1		%CaCO3	ASTM D 4373
Butane Act.	-0.5		g/100g dry	ASTM D 5742-95
Surface Area Correlation	118		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.41	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.16	J
Chromium	(Cr)	**ND**	93 to 1200	0.41	J
Cobalt	(Co)	**ND**	34 to 100	0.41	J
Copper	(Cu)	**ND**	143 to 6000	0.41	J
Lead	(Pb)	**ND**	121 to 300	0.16	J
Molybdenum	(Mo)	**ND**	5 to 75	0.41	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	2.3	47 to 420	0.41	J
Selenium	(Se)	**ND**	2 to 200	0.82	J
Zinc	(Zn)	2.5	416 to 7400	0.82	J
Boron	(B)	**ND**	Declaration	4.10	TMECC
Chlorine	(Cl)	30	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	409.8	E
Iron	(Fe)	70	Declaration	20.5	E
Manganese	(Mn)	7	Declaration	0.41	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	N/A	percent	F
0.5-1mm	N/A	percent	F
1-2mm	N/A	percent	F
2-4mm	N/A	percent	F
4-8mm	N/A	percent	F
8-16mm	N/A	percent	F
16-25mm	N/A	percent	F
25-50mm	N/A	percent	F
>50mm	N/A	percent	F

Basic Soil Enhancement Properties			
Total (K)	2166	mg/kg	E
Total (P)	10	mg/kg	E
Ammonia (NH4-N)	1.0	mg/kg	A
Nitrate (NO3-N)	1.2	mg/kg	A
Organic (Org-N)	7615	mg/kg	Calc.
Volatile Matter	6.0	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.12: **WPFM (95/5) 500C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Wood Pellets + LDPE File (95/5) at 500 C
Lab ID. Number: 0120576-13

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

Dry Basis Unless Stated:		Range	Units	Method
Moisture (time of analysis)	3.8		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	13.3		lb/cu ft	
Organic Carbon	83.0		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.52	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	1.9		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.39		% of total dry mass	Dry Combustion
pH value	11.12		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	0.123		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	4.3		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	1.1		%CaCO3	ASTM D 4373
Butane Act.	3.3		g/100g dry	ASTM D 5742-95
Surface Area Correlation	237		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.49	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.20	J
Chromium	(Cr)	**ND**	93 to 1200	0.49	J
Cobalt	(Co)	**ND**	34 to 100	0.49	J
Copper	(Cu)	3.2	143 to 6000	0.49	J
Lead	(Pb)	1.2	121 to 300	0.20	J
Molybdenum	(Mo)	**ND**	5 to 75	0.49	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	0.9	47 to 420	0.49	J
Selenium	(Se)	**ND**	2 to 200	0.98	J
Zinc	(Zn)	31.6	416 to 7400	0.98	J
Boron	(B)	8.5	Declaration	4.90	TMECC
Chlorine	(Cl)	**ND**	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	490.2	E
Iron	(Fe)	75	Declaration	24.5	E
Manganese	(Mn)	46	Declaration	0.49	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	N/A	percent	F
0.5-1mm	N/A	percent	F
1-2mm	N/A	percent	F
2-4mm	N/A	percent	F
4-8mm	N/A	percent	F
8-16mm	N/A	percent	F
16-25mm	N/A	percent	F
25-50mm	N/A	percent	F
>50mm	N/A	percent	F
Basic Soil Enhancement Properties			
Total (K)	2252	mg/kg	E
Total (P)	40	mg/kg	E
Ammonia (NH4-N)	0.4	mg/kg	A
Nitrate (NO3-N)	0.4	mg/kg	A
Organic (Org-N)	3933	mg/kg	Calc.
Volatile Matter	17.7	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.13: **WPFM (95/5) 650C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No: 11261
Batch: MAR 21 A
CODE: BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 3/1/2021
Sample ID: Wood Pellets + LDPE Film at 650 C (95/5) (WP95GM5 650C)
Lab ID. Number: 1030013-02

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

Dry Basis Unless Stated:		Range	Units	Method
Moisture (time of analysis)	3.8		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	19.1		lb/cu ft	
Organic Carbon	90.6		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.42	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	1.9		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.53		% of total dry mass	Dry Combustion
pH value	8.08		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	0.181		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	6.3		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	1.2		%CaCO3	ASTM D 4373
Butane Act.	2.1		g/100g dry	ASTM D 5742-95
Surface Area Correlation	201		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.43	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.17	J
Chromium	(Cr)	**ND**	93 to 1200	0.43	J
Cobalt	(Co)	**ND**	34 to 100	0.43	J
Copper	(Cu)	0.5	143 to 6000	0.43	J
Lead	(Pb)	**ND**	121 to 300	0.17	J
Molybdenum	(Mo)	0.9	5 to 75	0.43	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	**ND**	47 to 420	0.43	J
Selenium	(Se)	**ND**	2 to 200	0.86	J
Zinc	(Zn)	12.9	416 to 7400	0.86	J
Boron	(B)	5.6	Declaration	4.31	TMECC
Chlorine	(Cl)	22	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	431.2	E
Iron	(Fe)	49	Declaration	21.6	E
Manganese	(Mn)	5	Declaration	0.43	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	12.4	percent	F
0.5-1mm	17.3	percent	F
1-2mm	8.4	percent	F
2-4mm	9.3	percent	F
4-8mm	52.6	percent	F
8-16mm	0.0	percent	F
16-25mm	0.0	percent	F
25-50mm	0.0	percent	F
>50mm	0.0	percent	F

Basic Soil Enhancement Properties			
Total (K)	708	mg/kg	E
Total (P)	4	mg/kg	E
Ammonia (NH4-N)	3.8	mg/kg	A
Nitrate (NO3-N)	1.3	mg/kg	A
Organic (Org-N)	5284	mg/kg	Calc.
Volatile Matter	15.5	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.14: **WPFM (95/5) 800C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Wood Pellets + LDPE File (95/5) at 800 C
Lab ID. Number: 0120576-14

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

	Dry Basis Unless Stated:	Range	Units	Method
Moisture (time of analysis)	4.1		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	14.6		lb/cu ft	
Organic Carbon	92.3		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.23	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	2.3		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.74		% of total dry mass	Dry Combustion
pH value	7.22		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	0.520		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	5.3		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	2.1		%CaCO3	ASTM D 4373
Butane Act.	0.0		g/100g dry	ASTM D 5742-95
Surface Area Correlation	133		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.45	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.18	J
Chromium	(Cr)	**ND**	93 to 1200	0.45	J
Cobalt	(Co)	**ND**	34 to 100	0.45	J
Copper	(Cu)	**ND**	143 to 6000	0.45	J
Lead	(Pb)	**ND**	121 to 300	0.18	J
Molybdenum	(Mo)	**ND**	5 to 75	0.45	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	1.5	47 to 420	0.45	J
Selenium	(Se)	**ND**	2 to 200	0.90	J
Zinc	(Zn)	1.6	416 to 7400	0.90	J
Boron	(B)	**ND**	Declaration	4.50	TMECC
Chlorine	(Cl)	34	Declaration	20.0	TMECC
Sodium	(Na)	465	Declaration	450.5	E
Iron	(Fe)	54	Declaration	22.5	E
Manganese	(Mn)	7	Declaration	0.45	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	N/A	percent	F
0.5-1mm	N/A	percent	F
1-2mm	N/A	percent	F
2-4mm	N/A	percent	F
4-8mm	N/A	percent	F
8-16mm	N/A	percent	F
16-25mm	N/A	percent	F
25-50mm	N/A	percent	F
>50mm	N/A	percent	F

Basic Soil Enhancement Properties			
Total (K)	1816	mg/kg	E
Total (P)	2	mg/kg	E
Ammonia (NH4-N)	0.2	mg/kg	A
Nitrate (NO3-N)	0	mg/kg	A
Organic (Org-N)	7383	mg/kg	Calc.
Volatile Matter	3.0	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.15: **WPFM (75/25) 500C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Wood Pellets + LDPE File (75/25) at 500 C
Lab ID. Number: 0120576-11

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

	Dry Basis Unless Stated:	Range	Units	Method
Moisture (time of analysis)	3.5		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	18.1		lb/cu ft	
Organic Carbon	81.1		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.54	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	3.2		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.36		% of total dry mass	Dry Combustion
pH value	10.49		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	0.137		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	9.4		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	0.7		%CaCO3	ASTM D 4373
Butane Act.	3.3		g/100g dry	ASTM D 5742-95
Surface Area Correlation	238		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.49	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.20	J
Chromium	(Cr)	**ND**	93 to 1200	0.49	J
Cobalt	(Co)	**ND**	34 to 100	0.49	J
Copper	(Cu)	4.6	143 to 6000	0.49	J
Lead	(Pb)	1.4	121 to 300	0.20	J
Molybdenum	(Mo)	**ND**	5 to 75	0.49	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	1.5	47 to 420	0.49	J
Selenium	(Se)	**ND**	2 to 200	0.98	J
Zinc	(Zn)	151	416 to 7400	0.98	J
Boron	(B)	8.9	Declaration	4.90	TMECC
Chlorine	(Cl)	**ND**	Declaration	20.0	TMECC
Sodium	(Na)	504	Declaration	490.2	E
Iron	(Fe)	98	Declaration	24.5	E
Manganese	(Mn)	59	Declaration	0.49	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	N/A	percent	F
0.5-1mm	N/A	percent	F
1-2mm	N/A	percent	F
2-4mm	N/A	percent	F
4-8mm	N/A	percent	F
8-16mm	N/A	percent	F
16-25mm	N/A	percent	F
25-50mm	N/A	percent	F
>50mm	N/A	percent	F

Basic Soil Enhancement Properties			
Total (K)	2413	mg/kg	E
Total (P)	82	mg/kg	E
Ammonia (NH4-N)	0.3	mg/kg	A
Nitrate (NO3-N)	0.3	mg/kg	A
Organic (Org-N)	3631	mg/kg	Calc.
Volatile Matter	18.3	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.16: **WPFM (75/25) 650C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No: 11261
Batch: MAR 21 A
CODE: BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 3/1/2021
Sample ID: Wood Pellets + LDPE Film at 650C (WP75FM25 650C)
Lab ID. Number: 1030013-03

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

Dry Basis Unless Stated:		Range	Units	Method
Moisture (time of analysis)	4.5		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	20.7		lb/cu ft	
Organic Carbon	89.3		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.39	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	3.4		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.49		% of total dry mass	Dry Combustion
pH value	9.48		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	0.276		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	5.6		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	0.8		%CaCO3	ASTM D 4373
Butane Act.	0.5		g/100g dry	ASTM D 5742-95
Surface Area Correlation	149		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.39	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.16	J
Chromium	(Cr)	**ND**	93 to 1200	0.39	J
Cobalt	(Co)	**ND**	34 to 100	0.39	J
Copper	(Cu)	1.1	143 to 6000	0.39	J
Lead	(Pb)	0.5	121 to 300	0.16	J
Molybdenum	(Mo)	**ND**	5 to 75	0.39	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	0.4	47 to 420	0.39	J
Selenium	(Se)	**ND**	2 to 200	0.78	J
Zinc	(Zn)	114	416 to 7400	0.78	J
Boron	(B)	4.8	Declaration	3.92	TMECC
Chlorine	(Cl)	27	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	391.7	E
Iron	(Fe)	48	Declaration	19.6	E
Manganese	(Mn)	5	Declaration	0.39	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	11.3	percent	F
0.5-1mm	14.2	percent	F
1-2mm	8.2	percent	F
2-4mm	6.7	percent	F
4-8mm	59.6	percent	F
8-16mm	0.0	percent	F
16-25mm	0.0	percent	F
25-50mm	0.0	percent	F
>50mm	0.0	percent	F

Basic Soil Enhancement Properties			
Total (K)	734	mg/kg	E
Total (P)	25	mg/kg	E
Ammonia (NH4-N)	3.1	mg/kg	A
Nitrate (NO3-N)	2.1	mg/kg	A
Organic (Org-N)	4895	mg/kg	Calc.
Volatile Matter	11.1	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.17: **WPFM (75/25) 800C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No: 11261
Batch: DEC 20 D
CODE: BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Wood Pellets + LDPE File (75/25) at 800 C
Lab ID. Number: 0120576-12

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

Dry Basis Unless Stated:		Range	Units	Method
Moisture (time of analysis)	3.1		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	16.4		lb/cu ft	
Organic Carbon	91.0		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.24	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	3.6		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.74		% of total dry mass	Dry Combustion
pH value	8.04		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	1.09		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	5.5		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	1.5		%CaCO3	ASTM D 4373
Butane Act.	-0.1		g/100g dry	ASTM D 5742-95
Surface Area Correlation	131		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.47	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.19	J
Chromium	(Cr)	**ND**	93 to 1200	0.47	J
Cobalt	(Co)	**ND**	34 to 100	0.47	J
Copper	(Cu)	2.0	143 to 6000	0.47	J
Lead	(Pb)	**ND**	121 to 300	0.19	J
Molybdenum	(Mo)	0.5	5 to 75	0.47	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	0.5	47 to 420	0.47	J
Selenium	(Se)	**ND**	2 to 200	0.93	J
Zinc	(Zn)	6.6	416 to 7400	0.93	J
Boron	(B)	**ND**	Declaration	4.67	TMECC
Chlorine	(Cl)	**ND**	Declaration	20.0	TMECC
Sodium	(Na)	**ND**	Declaration	467.3	E
Iron	(Fe)	60	Declaration	23.4	E
Manganese	(Mn)	10	Declaration	0.47	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	N/A	percent	F
0.5-1mm	N/A	percent	F
1-2mm	N/A	percent	F
2-4mm	N/A	percent	F
4-8mm	N/A	percent	F
8-16mm	N/A	percent	F
16-25mm	N/A	percent	F
25-50mm	N/A	percent	F
>50mm	N/A	percent	F

Basic Soil Enhancement Properties			
Total (K)	1675	mg/kg	E
Total (P)	24	mg/kg	E
Ammonia (NH4-N)	0.3	mg/kg	A
Nitrate (NO3-N)	0.3	mg/kg	A
Organic (Org-N)	7370	mg/kg	Calc.
Volatile Matter	3.8	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.18: **Raw HB.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Raw Hammer Milled Boxboard
Lab ID. Number: 0120576-17

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

	Dry Basis Unless Stated:	Range	Units	Method
Moisture (time of analysis)	17.0		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	3.1		lb/cu ft	
Organic Carbon	44.9		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	2.35	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	3.7		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.21		% of total dry mass	Dry Combustion
pH value	7.91		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	0.339		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	4.6		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	1.7		%CaCO3	ASTM D 4373
Butane Act.	2.2		g/100g dry	ASTM D 5742-95
Surface Area Correlation	203		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.85	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.34	J
Chromium	(Cr)	5.5	93 to 1200	0.85	J
Cobalt	(Co)	**ND**	34 to 100	0.85	J
Copper	(Cu)	12.2	143 to 6000	0.85	J
Lead	(Pb)	3.1	121 to 300	0.34	J
Molybdenum	(Mo)	0.9	5 to 75	0.85	J
Mercury	(Hg)	**ND**	1 to 17	0.002	EPA 7471
Nickel	(Ni)	3.2	47 to 420	0.85	J
Selenium	(Se)	**ND**	2 to 200	1.69	J
Zinc	(Zn)	26.8	416 to 7400	1.69	J
Boron	(B)	42.4	Declaration	8.47	TMECC
Chlorine	(Cl)	141	Declaration	20.0	TMECC
Sodium	(Na)	1017	Declaration	847.5	E
Iron	(Fe)	377	Declaration	42.4	E
Manganese	(Mn)	38	Declaration	0.85	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	#DIV/0!	percent	F
0.5-1mm	#DIV/0!	percent	F
1-2mm	#DIV/0!	percent	F
2-4mm	#DIV/0!	percent	F
4-8mm	#DIV/0!	percent	F
8-16mm	#DIV/0!	percent	F
16-25mm	#DIV/0!	percent	F
25-50mm	#DIV/0!	percent	F
>50mm	#DIV/0!	percent	F

Basic Soil Enhancement Properties			
Total (K)	358	mg/kg	E
Total (P)	74	mg/kg	E
Ammonia (NH4-N)	6.7	mg/kg	A
Nitrate (NO3-N)	6.6	mg/kg	A
Organic (Org-N)	2037	mg/kg	Calc.
Volatile Matter	81.4	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.19: **HB500C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Hammer Milled Boxboard at 500 C
Lab ID. Number: 0120576-18

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

Dry Basis Unless Stated:		Range	Units	Method
Moisture (time of analysis)	16.2		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	2.4		lb/cu ft	
Organic Carbon	69.1		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.71	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	11.2		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.37		% of total dry mass	Dry Combustion
pH value	8.95		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	0.254		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	7.9		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	2.7		%CaCO3	ASTM D 4373
Butane Act.	2.6		g/100g dry	ASTM D 5742-95
Surface Area Correlation	215		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.46	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.19	J
Chromium	(Cr)	5.0	93 to 1200	0.46	J
Cobalt	(Co)	0.7	34 to 100	0.46	J
Copper	(Cu)	24.1	143 to 6000	0.46	J
Lead	(Pb)	8.1	121 to 300	0.19	J
Molybdenum	(Mo)	0.8	5 to 75	0.46	J
Mercury	(Hg)	**ND**	1 to 17	0.002	EPA 7471
Nickel	(Ni)	2.7	47 to 420	0.46	J
Selenium	(Se)	**ND**	2 to 200	0.93	J
Zinc	(Zn)	55.2	416 to 7400	0.93	J
Boron	(B)	94.9	Declaration	4.63	TMECC
Chlorine	(Cl)	43	Declaration	20.0	TMECC
Sodium	(Na)	2542	Declaration	463.0	E
Iron	(Fe)	838	Declaration	23.1	E
Manganese	(Mn)	86	Declaration	0.46	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	#DIV/0!	percent	F
0.5-1mm	#DIV/0!	percent	F
1-2mm	#DIV/0!	percent	F
2-4mm	#DIV/0!	percent	F
4-8mm	#DIV/0!	percent	F
8-16mm	#DIV/0!	percent	F
16-25mm	#DIV/0!	percent	F
25-50mm	#DIV/0!	percent	F
>50mm	#DIV/0!	percent	F

Basic Soil Enhancement Properties			
Total (K)	371	mg/kg	E
Total (P)	184	mg/kg	E
Ammonia (NH4-N)	0.6	mg/kg	A
Nitrate (NO3-N)	0.7	mg/kg	A
Organic (Org-N)	3659	mg/kg	Calc.
Volatile Matter	24.6	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.20: **HB800C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Hammer Milled Boxboard at 800 C
Lab ID. Number: 0120576-19

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

	Dry Basis Unless Stated:	Range	Units	Method
Moisture (time of analysis)	12.8		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	2.5		lb/cu ft	
Organic Carbon	76.2		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.40	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	16.0		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.66		% of total dry mass	Dry Combustion
pH value	11.98		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	6.52		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	4.7		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	2.2		%CaCO3	ASTM D 4373
Butane Act.	2.6		g/100g dry	ASTM D 5742-95
Surface Area Correlation	215		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.48	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.19	J
Chromium	(Cr)	4.5	93 to 1200	0.48	J
Cobalt	(Co)	0.9	34 to 100	0.48	J
Copper	(Cu)	20.7	143 to 6000	0.48	J
Lead	(Pb)	0.8	121 to 300	0.19	J
Molybdenum	(Mo)	1.4	5 to 75	0.48	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	3.4	47 to 420	0.48	J
Selenium	(Se)	**ND**	2 to 200	0.96	J
Zinc	(Zn)	6.1	416 to 7400	0.96	J
Boron	(B)	56.2	Declaration	4.81	TMECC
Chlorine	(Cl)	131	Declaration	20.0	TMECC
Sodium	(Na)	2541	Declaration	480.8	E
Iron	(Fe)	1076	Declaration	24.0	E
Manganese	(Mn)	62	Declaration	0.48	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	#DIV/0!	percent	F
0.5-1mm	#DIV/0!	percent	F
1-2mm	#DIV/0!	percent	F
2-4mm	#DIV/0!	percent	F
4-8mm	#DIV/0!	percent	F
8-16mm	#DIV/0!	percent	F
16-25mm	#DIV/0!	percent	F
25-50mm	#DIV/0!	percent	F
>50mm	#DIV/0!	percent	F

Basic Soil Enhancement Properties			
Total (K)	421	mg/kg	E
Total (P)	118	mg/kg	E
Ammonia (NH4-N)	1.1	mg/kg	A
Nitrate (NO3-N)	1.4	mg/kg	A
Organic (Org-N)	6632	mg/kg	Calc.
Volatile Matter	8.4	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.21: **PW500C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Pallet Wood at 500 C
Lab ID. Number: 0120576-15

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

	Dry Basis Unless Stated:	Range	Units	Method
Moisture (time of analysis)	5.6		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	7.9		lb/cu ft	
Organic Carbon	78.7		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.66	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	2.2		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.75		% of total dry mass	Dry Combustion
pH value	7.24		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	0.100		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	3.4		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	0.7		%CaCO3	ASTM D 4373
Butane Act.	2.3		g/100g dry	ASTM D 5742-95
Surface Area Correlation	205		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	1.5	13 to 100	0.49	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.20	J
Chromium	(Cr)	2.0	93 to 1200	0.49	J
Cobalt	(Co)	**ND**	34 to 100	0.49	J
Copper	(Cu)	13.8	143 to 6000	0.49	J
Lead	(Pb)	5.2	121 to 300	0.20	J
Molybdenum	(Mo)	**ND**	5 to 75	0.49	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	1.5	47 to 420	0.49	J
Selenium	(Se)	**ND**	2 to 200	0.98	J
Zinc	(Zn)	37.9	416 to 7400	0.98	J
Boron	(B)	15.3	Declaration	4.90	TMECC
Chlorine	(Cl)	**ND**	Declaration	20.0	TMECC
Sodium	(Na)	543	Declaration	490.2	E
Iron	(Fe)	1845	Declaration	24.5	E
Manganese	(Mn)	180	Declaration	0.49	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	#DIV/0!	percent	F
0.5-1mm	#DIV/0!	percent	F
1-2mm	#DIV/0!	percent	F
2-4mm	#DIV/0!	percent	F
4-8mm	#DIV/0!	percent	F
8-16mm	#DIV/0!	percent	F
16-25mm	#DIV/0!	percent	F
25-50mm	#DIV/0!	percent	F
>50mm	#DIV/0!	percent	F

Basic Soil Enhancement Properties			
Total (K)	2109	mg/kg	E
Total (P)	220	mg/kg	E
Ammonia (NH4-N)	0.5	mg/kg	A
Nitrate (NO3-N)	0.3	mg/kg	A
Organic (Org-N)	7534	mg/kg	Calc.
Volatile Matter	20.8	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge

APPENDIX B.22: **PW800C.**

Control Laboratories
42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No:
11261
Batch:
DEC 20 D
CODE:
BioChar IBI

Thomas Trabold
Golisano Institute for Sustainability
190 Lomb Memorial Drive
Rochester, NY 14623

Date Received: 12/18/2020
Sample ID: Pallet Wood at 800 C
Lab ID. Number: 0120576-16

International BioChar Initiative (IBI) Laboratory Tests for Certification Program

	Dry Basis Unless Stated:	Range	Units	Method
Moisture (time of analysis)	4.5		% wet wt.	ASTM D1762-84 (105c)
Bulk Density	9.5		lb/cu ft	
Organic Carbon	89.3		% of total dry mass	Dry Combust-ASTM D 4373
Hydrogen/Carbon (H:C)	0.26	0.7 Max	Molar Ratio	H dry combustion/C(above)
Total Ash	3.8		% of total dry mass	ASTM D-1762-84
Total Nitrogen	0.99		% of total dry mass	Dry Combustion
pH value	11.33		units	4.11USCC:dil. Rajkovich
Electrical Conductivity (EC20 w/w)	1.38		dS/m	4.10USCC:dil. Rajkovich
Liming (neut. Value as-CaCO3)	5.3		%CaCO3	AOAC 955.01
Carbonates (as-CaCO3)	2.5		%CaCO3	ASTM D 4373
Butane Act.	0.5		g/100g dry	ASTM D 5742-95
Surface Area Correlation	149		m2/g dry	G

All units mg/kg dry unless stated:		Results	Range of Max. Levels	Reporting Limit (ppm)	Method
Arsenic	(As)	**ND**	13 to 100	0.43	J
Cadmium	(Cd)	**ND**	1.4 to 39	0.17	J
Chromium	(Cr)	1.0	93 to 1200	0.43	J
Cobalt	(Co)	**ND**	34 to 100	0.43	J
Copper	(Cu)	5.8	143 to 6000	0.43	J
Lead	(Pb)	0.7	121 to 300	0.17	J
Molybdenum	(Mo)	**ND**	5 to 75	0.43	J
Mercury	(Hg)	**ND**	1 to 17	0.001	EPA 7471
Nickel	(Ni)	0.9	47 to 420	0.43	J
Selenium	(Se)	**ND**	2 to 200	0.86	J
Zinc	(Zn)	6.4	416 to 7400	0.86	J
Boron	(B)	15.6	Declaration	4.31	TMECC
Chlorine	(Cl)	33	Declaration	20.0	TMECC
Sodium	(Na)	485	Declaration	431.0	E
Iron	(Fe)	743	Declaration	21.6	E
Manganese	(Mn)	39	Declaration	0.43	J

Particle Size Distribution	Results	Units	Method
< 0.5mm	#DIV/0!	percent	F
0.5-1mm	#DIV/0!	percent	F
1-2mm	#DIV/0!	percent	F
2-4mm	#DIV/0!	percent	F
4-8mm	#DIV/0!	percent	F
8-16mm	#DIV/0!	percent	F
16-25mm	#DIV/0!	percent	F
25-50mm	#DIV/0!	percent	F
>50mm	#DIV/0!	percent	F

Basic Soil Enhancement Properties			
Total (K)	1510	mg/kg	E
Total (P)	106	mg/kg	E
Ammonia (NH4-N)	3.6	mg/kg	A
Nitrate (NO3-N)	0.3	mg/kg	A
Organic (Org-N)	9855	mg/kg	Calc.
Volatile Matter	5.5	percent dw	D

* "ND" stands for "not detected" which means the result is below the reporting limit.

Method A Rayment & Higginson
D ASTM D1762-84
E EPA3050B/EPA 6010
F ASTM D 2862 Granular
G Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
J EPA3050B/EPA 6020

Analyst: Nik Zumberge